VRIL COMPENDIUM

VOLUME 11

VRIL AND ELF DEVICES

VASSILATOS

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VOLUME 11

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COMMENTARY

For Victor and Mary

night parties, starbooks, and rockets

you were kind to listen

VOLUME 11

VRIL AND ELF DEVICES

11.1 SPACE PERMEATING ARTICULATIONS

The theme of this Compendium Volume is again to equate Vril dynamics with the historical development of technology. We will see that Vril dynamics, conscious and sensual in nature, appropriate the technologies which we develop for a more fundamental process. Despite our own technological predilections and thematic fixations the Vril Matrix reveals its noumenous presence, projecting successive regimes of consciousness on behalf of all bioorganisms. We have shown that the Matrix itself is the external conscious seat of world experience. Technologies having antagonistic relationship with this Matrix are proliferated on a worldwide front. Their influence upon the Matrix and bioorganismic integrity stands in question. It is therefore of utmost importance that we first comprehend our place in the conscious Vril Matrix. Knowing this place, we may then begin undertaking better exploratory means through which to extend our experiential and conscious range in that Matrix.

Vril is the ground of being. The Matrix is the articulate structure which Vril develops, the inhabitable domain in which bioorganismic generation is sustained. The Matrix is that region in which consciousness exists and can be received. The most direct way in which we conceive the world comes through our immediate experience. This immediate experience is ordinarily one which is location-limited. Immediate experience focusses in distinct externally generated centers, termed DIORAMAS. We can experience large portions of the whole world structure, gaining access to this experience through specific Vril Axes. Normally however, our experience is the interblend between auric projections in a diorama. To honestly describe our world from this vantage does not produce heliocentric models. Eidetic experience does not reveal a heliocentric world. Eidetic experience reveals a geocentric world.

Auric expansions determine our experience in any location. We perceive the deepest world experience through auric projections. These projections emerge from the Matrix and suffuse our being, our auric anatomy. They are eidetic suffusions of various kinds, a conjugate procession. Receiving these highly densified eidetic suffusions gives us experience. We also reproject the suffusions which flow through us out into the world dioramas. We are thus thoroughly intermeshed within the Vril Matrix. Experience is a dynamic exchange, a transaction between the Matrix and our own auric anatomy. Changes which begin in the Matrix are experienced immediately in sentient beings. Instrumentalities which effect modifications in the Matrix effect changes in every district-connected sentient being.

Eidetic experience is gained through the aura. Eidetic experience is composed of distinct and related dioramas, districts, and regions...in that order. Our own experiential range extends only when we connect with successive district

permeating Vril Axes. Immediate experience therefore begins with focalized dioramas. These experiential dioramas orient and supply our being. Within the world dioramas we perceive parts, termed "gestalten" by some early researchers.

Gestalten are conscious or "conceptual portions" which, from infancy, help form our experiential process. In the saccadic examinations of objects, we evidence our own conscious emergence through the shell of our inertialized anatomy. Saccades reveal the manner in which our externally absorbed consciousness makes its way, in thready projections, through the inertial shell. Called "visual rays" by certain Victorian researchers. The degree to which our pure auric anatomy breaks through this physiological shell determines our success as sensitives. Gestalten do not reveal that objects are made of parts. The parts are observed by our minds only as our consciousness examines the functional integrity of each whole created object. Dioramas are whole, created whole in the externally conceived visionary projection. The whole nature of created things may be contrasted against our own partitial conscious process in a simple personal experiment. By gazing at any object, we will observe how that object seemingly "breaks up" in discretely examined parts. In this process, consciousness contacts and focusses into specific portions of objects.

The flow of eidetic information along the visual ray fulfills certain auric nutritive requirements of which we yet have little understanding. When that required eidetic flow is completely absorbed, the visual ray quickly moves to examine yet another portion of the object. This visual ray movement manifest as rapid saccadic ocular movements, each auric absorption taking a small fraction of a second. In this study of visual rays, the thready auric projections of our consciousness, we will comprehend the whole thesis contained in this Compendium Volume.

One may gaze long at a figurine or statuette, watching the constant flicker of awareness as it examines gestalten. One sees, for example, a particular feature into which we are suddenly absorbed. During this time period, the other features of the figurine become blurred, as if somehow insignificant. Nevertheless this momentary point absorption ceases, and another is quickly found. The process occurs until the mind has reached a saturate eidetic potential, after which time we have successfully absorbed what eidetic nutritive value we can receive through the gazing act. Infants perform this rudimentary eidetic function throughout the many months of their preparation. It is fascinating to note that the saccadic examination of objects proceeds among specific points in the object, evidencing that generative Vril threads penetrate objects along specific axes.

When this remarkable fact is understood from the generative view, one recognizes that objects "blossom" or expand out from these generative points. Objects each reveal an intriguing and distinctive series of conscious foci, identical elements and substances always showing very different populations and orientations of the focal points. It is wondrous to note how we are drawn into these microalignments. Objects thus evidence deeper-than-atomic existence, emerging from conscious

foundations. But these studies require closer examinations which will be presented in a future Compendium Volume on Material Eidoactivity. Experiential dioramas are whole creations. Within these dioramas, we are able to identify certain forms, symmetries, and structures. Comparisons among dioramas reveal similarities and repetitions which evidence a fundamental compositional commonality, termed ARCHETYPES by certain conceptualists.

Vril sends the Archetypes. The archetypal composition of each diorama gives us insight into Vril itself, presenting something of the developmental history contained in contemporary Vril currents. Vril permutes, surmounting its previous states with unexpected new manifestations. Each successive Vril permutation contains within itself all the previous developmental aspects in amalgamated form. Archetypes are actually primal forms which demonstrate the permuted developments of Vril. These each began in the countless previous aeons of consciousness. Vril space is consciousness, both continuously generating and projecting consciousness. Vril has external distributions which may be mapped. Vril currents suffuse the ground from archaeozoic depths which exceed geological scope, being metaphysical foundations. The world is founded on consciousness, not matter.

Vril visionary experience reveals that metaphysical foundations, not inertial ones, found the experiential topography in which we have our being. The black radiance is most powerfully concentrated in the ground; layers and strata of world generative Vril. Vril strata evidence mysterious pulsating tides throughout the seasons. The ancient geomancers were familiar with all of these realities, a worldview gained from direct visionary experience. The objective existence and continuance of the material world evidences an EXTERNAL CONSCIOUSNESS which is both generative and projective. Experience is fundamentally EIDETIC in nature. This eidetic experience was once named "Astral" experience, the result of perception in the "Astral Space". This external consciousness expresses a visionary thesaurus, images which we have come to recognize as our world. It is a supernal generator. Vril is the world domain in which metaphysical and physical find juncture. The Vril World, the real World, cannot be discovered through any but direct means. Vril must suffuse the percipient, opening new consciousness. The world is not founded on matter. The world is founded on consciousness.

As inertial space is dissolved around a focussed Vril channel one suddenly experiences the flood of consciousness which is Vril Space, a seething sea of eidetic treasures and organized thought process. In this manner we translate out of inertial space, the bound expression which academes prize, and enter the image floods of Vril Space. In Vril Space, the articulate matrix of consciousness, we find the continual flood of those experiences termed "metaphysical" and "imaginal". These are the suppressed communications from which the world is generated and sustained, a suffusive presence which upholds the experiential world. In this is comprehended the worldview which the ancients espoused, a world which confessed that consciousness is more fundamental than matter. Ideation, emotion, thought, archetype,

vision, dream, fantasy, those currents which academes judge to unreal and internal, are all found in the Vril Matrix. These comprise the fundamental modes by which children and sensitives experience world communion. It is the world which children retain for a few precious years before inertial space absorbs portions of their sense and mind, dulling them to the sparkling dreamtides which incessantly surge in the Vril Matrix.

For the academe, thoughts are produced by neurochemicals. For them, consciousness is a familiar chemical pattern which is replete with metaphysical "noise". Taken in our well founded worldview, it is obvious why their world assessment is so sharp, final, and limited. Theirs is a science which makes observation in a captive inertial space; one whose dynamics are effects, completely dependent upon primary Vril directives. The assembled collection of dynamics which comprises academic physics is a study of the enveloped inertial space. Inertial space is not the whole of space. This is evident from common consciousness of common experience, through which the material of the world is made known.

Before there is matter there is mind. Consciousness remains the door. What academes have successfully managed is a dialogue in which sense restrictive laws and the placement of conscious barriers is first established. The second part of their dialogue examines the resultant effects of dividing human experience. Their divisions are completely arbitrary, lacking antagonists only because so few can sensitively discern such philosophical distinctions. Those with whom they differ are cast out of their consortium, a pseudoreligious hierarchy of clever profiteers who operate through yesmanship. The consciousness by which academes constructed their quantitative rules precedes those rules...and can disannul the arbitrary rules at any time. Basing this credo on inertial dynamics however, academes are bound to sense restrictive rules by which "boundaries in experience" are enforced. They insist on their worldview despite the self-annihilating results.

The essence of academic refusal to engage purely subjective and qualitative world examinations is based on the arbitrary placement of boundaries in conscious experience. Otherwise whole and undivided, our common world experience flows in conscious currents by which we are in complete fusion with the external. We have adequately discussed the simple means by which personal consciousness can be proven to be the result of external conscious dynamics (V.8). In this we have seen that personal consciousness is a process of RECEPTION, and not one of autonomous manufacture. Personal consciousness shares in the flowing images and thoughtstreams of which the whole external space is fundamentally comprised. It is from this sea of eidetic energies that both the solid world and we ourselves draw our being.

The absolute fixed axes of the referential world structure are discovered in world examinations made through conscious parameters alone. Inertial meters do not respond to these suffusive energies, which require bioarticulate reception. Biological organizations, neurosystems especially, recognize,

absorb, engage, experience, and participate in the imaginal sea...the true space. Ultimately important in our discussion is the realization that both the world and the experience of the world are conscious emanations which proceed from an EXTERNAL agency. This is why the world has continued and "objective" existence, being continuously sustained by the flood of eidetic energy. But, in this consideration, we cannot recognize conscious boundaries by which to separate self from world, internal from external.

The only boundaries which consciousness recognizes are determined by preordained axes which permeate experiential space, and direct conscious attentions. Boundaries which consider inertia are clearly divisional, based on touch and sight but not on consciousness. In the greatest consideration, inertial space is only an invasive agency. It is a dead zone, whose permeating presence occludes complete Vril engagements. It is therefore an incomplete consciousness, robbing those who pursue of experiential joy, sensation, and world communion. Inertial consciousness progressively leads to death.

Inertial expressions cover a range of manifestations which academic science does not properly classify as such. All inertial components in the environment (pressures, momenta, fields, particles, forces) are the result of Vril penetrations through the inertial space. At the core of each of these phenomena, one finds the fundamental black radiance. The unfortunate schism which deranged scientific pursuits placed emphasis on the wrong components of phenomena. Rather than examining the vital qualities which suffuse the world, science began seeking knowledge of the inertial detritus which accompanies Vril expressions in the terrestrial environment. Academia thus chose the study of quantitative rather than qualitative phenomena. With this revision came the revilement of human sensation, the preference of inert measuring tools over subjective experience. It was thus that the human sensorium, our providential access into Vril world reality, was reviled in favor of alienating mechanisms.

Inertia is the occlusive and resistant medium which binds the free expression of Vril, the biodynamic generator. Whether naturally or deliberately, dissolved inertia releases magnified conscious states to us. This is why it is imperative for us to learn more of the Vril nature; developing systems for the expressed purpose of dissolving the inertial occlusions which occupy so much of our world. External consciousness is the eidetic sea from which the world is generated, and in which it is sustained. One has only to close the eyes to recognize that consciousness persists despite the removal of the world-probing senses. With the eyes closed, one recognizes that all thought and ideational imagery does not cease with the eradication of external awareness. In fact, sensory deprivation results in an intensification of consciousness (Lilly).

Our individual consciousness is a shared experience, an energy which is wholly received from the outside. Our consciousness is the simple proof that the world is suffused in a sea of consciousness. This persistent consciousness is the world-

suffusing foundation, the very deepest nature and origin in which world observations must be made. Apart from this conscious space, this origin point, this ultimate cause, all other observations are superficial effects. This primary consciousness which capably examines the world has the very deepest vision as its fundamental sensory gate. The ancients called it mindvision. As one peers into matter, one experiences various sensations, transitions, phases. As one peers into matter, one receives impressions, images, ideas, revelations. The ancients realized the most sublime truth. Suffused in the generative consciousness, the world exists.

Observations which are made with the mind reveal a world which differs from that which is obtained through the other senses. It is possible to observe the world through the senses, devoid of consciousness. In fact, when captivated by the world and its dynamics, one experiences a cessation of consciousness. Such non-conscious sense examinations of the world form the very basis of quantitative science. The discipline of exceptional conscious awareness was required before philosophers would permit themselves the simplest empirical examinations of the world. Deeply aware that non-conscious examinations would bring falsehood into their minds, most grew increasingly distant from the discipline itself. Intended to suffuse consciousness throughout the body, permitting complete fusion with sense examination, philosophy grew to reject the world matter in favor of the ideal which its mind perceived.

Pythagoras taught a method through which consciousness could be actively suffused into sensory examinations, bringing new appreciation for the presence of the ideal world within the physical world. His methods utilized mind-magnifying devices...musical instruments...through whose application it was possible for both individuals and groups to enter new and suffusive mindstates. In these states, world examinations could be made with great ease. Pythagoras discovered that specific scales and repetitious tones could so dissolve the world resistance, that a persistent and suffusive energy would appear. The "rhizomes", resounding and ringing tones, flooded places where these experiments were undertaken. Pythagoras discovered that specific groundpoints permitted especially rapid and sustained entrances into these magnified mindstates, always the sacred places which were anciently revered. His development of special theatrums had as its aim the literal conversion of conscious space on behalf of a large participatory consortium.

The simple knowledge that our consciousness is an externally generated energy, one which is absorbed into our being from surrounding space was anciently revered as truth. Those exceptional receptions of idea and vision, common to all sentient beings, were observed with all reverence and devotion. The knowledge that space was suffused by a vast consciousness was not considered a strange and derided notion. The very mention of such a singular conception was not attended by blasphemous responses. Nevertheless, this was the foundation on which ancient science stood. It chose consciousness itself as its fundamental observational base. Ideas and ideational images were considered

divine utterances (Socrates). There was no debate concerning the validity of the mind. For the ancients, the mind could peer into matter and perceive the archetypes and divinely ordained forms.

Pythagoras came closest to the long-forgotten truths concerning consciousness and the means for achieving magnified mindstates. It was recognized that philosophic discipline, an arduous and demanding personal process, was objectionable to most persons of moderate intelligence. Pythagoras realized that instrumental means could effectively and quickly achieve what the arduous disciplines could not. Continued saturation in musical energies brought elevated mindstates to large numbers of individuals; individuals who yearned for a greater world. Those persons moved Pythagoras with a special devotion. He determined to grant them some aid in their personal quest.

It is obvious that the yearnings of needy minds were fulfilled in the method of Pythagoras, whose teachings are replete with special knowledge concerning the world-structure. More important, the Pythagorean school and method placed reliance on the utilization of INSTRUMENTS for dissolving inertial space and entering the magnified awareness through which came gratifying communion with the deepest accessible foundation. The use of instrumental aid permitted the Pythagorean Academy to rapidly achieve conscious states which were otherwise impossible to reach. One follows the developmental steps of ancient science through such knowledge with renewed vigor; recognizing the mark of consciousness magnifying INSTRUMENTS when examining archaeological artifacts and sites.

The later development and implementation of conductive instruments during the Twentieth Century evidenced the appearance of a new Vril permutation. This established consciousness in a new vector, a direction of developments which led to Radionic Science. Mind-permeating space topographies reveal the external and suffusive structure of the world. This structure can be dynamically modified by the application of special Radionic instruments. Collectively these instrumentalities, and their special components, comprise Vril Technology.

11.2 VRIL AND TECHNOLOGY

Ancient sensitives recognized the existence of spacial places where experience and consciousness seemed especially heightened. These became the resort of others whose sensitivities permitted extraordinary realizations, the receptions of projective energies there extant. Such sacred spots were justly revered as the natural oracles, geological vents from which divine utterance was prolific. Evident in the plethora of revelations stimulated in these locations alone, priestly castes developed to serve the sacred sites. This caste was not restricted to gender. Each such priestly caste observes the noumenous sacred spots with especial regard for the black radiant light which emerges at these locations. Typified throughout the mythological treasuries of the ancient cultures (Egyptian, Babylonian, Greek, Persian, Chinese) is the persistent mention of the black radiance. It is always associated with creative generation and consciousness. It is the ground of being from

which emerge all created things. Is it coincidental that we find black radiant projections throughout nature, energies which stimulate the reception of externally generated ideations?

Black radiance was equated with the divine. Black radiance was equated with remarkable favor. It was the means by which the culture survived against the wildness and savagery of life-killing natural forces. It was for this reason that the black radiance was sought and revered. Cultures knew that their very survival depended on the reception of this creative and providential energy. Ancient sensitives discovered that their own visionary prowess enlarged with repeated exposures to the black radiance, being often infused in contact at their anciently established sacred spots. The creative black radiance was often recognized emerging through trees and other such organic transducers. During times of cultural excess, these sites became excessively ornamented and weighed down by needless liturgies and superstitious service, none of which served to accelerate or enhance the naturally prolific flood of eidetic impressions received therein. Those whose consciousness was sufficiently raised to appreciate these simplistic realizations, managed the continuous reception of ideas, images, impressions, and revelations.

At first, special groups of attendant individuals were employed to memorize and retell the impressions received during such moments of magnified and clarified consciousness. In this means, cultures emerged from tribal groups. The implementation of ideas received reveals an intriguing process which is at work in ever cultural group thus developed. The appearance of sudden new ideas is thus linked to the priestly caste, who in turn are linked to their sacred spots. The sacred spot is the constant feature in each cultural centre, the physical location from which metaphysical thesaurus springs on behalf of the culture. It wa sin this manner that writing first appeared. The concept of equating written symbols with sounds or ideas was not the result of an ordinary thought process. With these developments, scribes were later employed to write down the impressions received by priest-sensitives.

A sudden flood of impressions appears in each such culture, impressions whose import brings knowledge of technology. But this renaissance of emerging ideations has a thematic content which exceeds the mere brancate development of writing, metallurgy, and stonecraft. The projection of these technological means are always historically linked to a massive **cultural effort**...a project in which the entire culture is consciously united. The aim of the **cultural project** is not simply one which establishes and solidifies social castes. It is not focussed on dominations and masteries. The project is one which promises to elevate the culture in matters of the mind. Mind expansions. The emergence of mind expanding technologies marks the emerging culture as a civilization. Contact at specific groundpoints with the emergent black radiance yet opens new awareness. The black radiance is the juncture of metaphysical and physical world. Black radiant sacred spots are the places from which consciousness actually emerges, the external projective sources which supply the world mind.

Adequately validating and explaining the wondrous prowess which archane visionaries demonstrated, first technology was Vril technology. It was by several simple means, each derived through progressive revelatory images, that magnified Vril energies were secured by certain archane societies. The special technology, given through Vril eidetic impressions, was the result of intimate personal contact with natural Vril currents. This was a technology whose components did nothing more than conduct and clarify Eidetic Vril Imagery. Vril was the energy. Archane societies grew ultimately more sensitive with continued Vril exposures and saturations. The concept of "working function" was exclusively defined as one having power to modify the mind. By this definition, only those potent did not require their technologies to manifest behaviors which were otherwise associated with purely inertial devices. Evidence of "working function"...movements, rotations, and sounds...was thus completely biased in inertial parameters by those who designed MACHINES. The machine, as commonly conceived, is not a Vril artifice.

The primary and fundamental domain in which Vril Technology operates, that for which it is alone designed, remains entirely within the domain of eidetic currents. Vril instrumentalities convey eidetic experiences to their operators, the most vital utility obtained through any technological artifice. Vril instruments are passive conductors and transducers of Vril currents. Human operators receive the potent efflux of these instrumentalities, being effectively changed into more extensive and elevated conscious states. Vril components do not fluoresce, burn, vibrate, or move as inertial engines do. For this reason, nonsensitives derided Vril Technology as useless.

Vril technologies project fluorescence, project heat, project cold, project sounds, project imagery, project levitations...indeed project and flood local spaces with any quality desired. When once adequate knowledge of these means are secured, Vril Technology can provide a far greater display of effects than autonomous inertial machines can ever hope to achieve. The most ancient natural oracular sites lack the power which is found in carved stone systems. These in turn lack the power which is obtained through Radionic artifice. Ancient systemologies are not abandoned, but certainly do not represent the most recent Vril expressions. They therefore lack the clarity and power of Vril now. One must seek the most recent Vril expressions in order to find the current Vril movement.

Each Vril system expansion contains within itself numerous stages and continual modifications; the evidence of a developing Vril growth process. Each developmental stage can catalyze the sudden appearance of some new permutation. This is the aspiration of the greatest and most actualized Vril engineers. Our investigation of these marvelous permutations began with discussions concerning electrical science. This recent movement did not divorce itself from the principles upon which the most ancient Vril systems were based. But, not limited to their more archaic forms, the new systemologies feature defined components; through which deeper and more clarified Vril conductions are

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obtained. From its inception electrical science has been overshadowed by Vril. This persistent Vril pursuit can be marked throughout both the development and implementation of electrical systems as major social technology. At times antagonistic, at times conformant, electrical systemologies have been haunted by Vril generated anomalies. These have also consistently haunted scientific dogma whenever that lexicon fails to account for Vril and the phenomena which accompany the Vril Domain.

The great number of contributors offers staggering testimony to a massive technological onslaught in which humanity was enveloped from the Mid-Nineteenth Century until the early Twentieth Century. The technological phenomenon which Vril stimulates in the world has never ceased. Those societies which forsook this power were eliminated from the historical record through extinctions. History itself bears evidence that the overpowering Vril influence had drawn human consciousness to its cooperations, giving consciousness in ever elevated degrees. Having been so drawn, human agents recognized the providence at work in their discoveries. The energy which guided their efforts was giving them superior understanding and greatly magnified awareness. This remarkable effects became the driving force behind RADIONICS, the study of natural radiances and their effect on human experience.

The mass mobilizing power of this energetic guidance had once drawn whole societies into its wonderful cooperations throughout the previous centuries. Experimenters began again to identify the energetic currents responsible for superior translations of mind. All this research began in the greatest universities, a most opened expression of scientific curiosity. The topic areas were isolated, rejected, and cast out of the university milieu. Suggesting that this qualitative approach to the world was somehow "irrational", academic science launched itself headlong into a frightening fall through objectivism. So deep did this process take the best scientific minds, that while alienating themselves from the experimental process, they imagined themselves in possession of greatest wisdom. Alienated, isolated, separated forever from the nature upon which they were intently focussed, only a very few managed to sense the cold and inert mindstate of their newfound poise. Nevertheless, the process continued without the academes, selectively isolating them from its wonders. Private researchers took up the work, funding their own laboratories and making history.

Observed by archane sensitives, black radiant Vril suffuses the natural world. It appears as a suffusive and uniform glowing space of deepest black atop special ridges and in some valleys. Here it most certainly always rises from the ground at night, where it is both seen and felt. Seeming very much to be a mysterious concentration of the winter's night sky on earth, ancient people reverenced these appearances. First contact within this radiant blackness always brings vital renewals. In human experience, these renewals span the gap between healings of body, mind, and soul, as well as the impartation of excited consciousness. Continued exposures in the black suffusions produce exceptional awareness. Such clarity of mind is yet

obtained through this natural agency that one recognizes in it an EXTERNAL distribution of consciousness throughout space.

It was anciently observed that powerful black radiant channels discharge between rock canyon walls, among boulders and trees, into and from certain caverns, and from ground to space. Poised among, within, atop the natural places where such energies pulsate, ancient sensitives received penetrating impressions and eidetic images. These primary receptions formed the basis of a new mindraising technology. Modelled from its natural manifestations, ancient geomancers constructed dolmens and mounds for the expressed purpose of securing the permanence of a black radiant presence. Structured in the grand scale of natural expressions, megalithic age technology effectively obtained for human tribes a new means...for permanently raising, maintaining, and employing their new consciousness.

Providing magnified forms of consciousness, Vril Technology has marked every major human endeavor. Raised consciousness was the survival of any human tribe. Tribes became societies, societies became cultures, and cultures became civilizations when black radiant energy was their source. Now constructed with deliberation, the new mindraising technology supplied humanity with survival at the most fundamental level. It is the silent revolution preceding every material advancement which famed histories chronicle. Developing such technology worked with the supernal distributed intelligence. Archaic developers of black radiant technology rebuilt the fallen sites where the glowing black radiance was naturally manifested. The purpose of these human-assisted developments was the world-magnification of conscious energy, a thrilling theme which returns as an echo among the ages.

When humanity follows the lead of VRIL, then new mindstates are achieved for humanity. When humanity loses the Vril thread, it is nevertheless drawn along to a future encounter with Vril realities. In this latter case, technologies which were developed for inertial employment manifest a mysterious Vril function with very minor modifications.Ancient megaliths, dolmens, and mounds formed the components of the archaic mindraising technology. Through certain rediscovered natural functions, these structures were empirically established for the exchange of eidetic messages among the sensitives. While many of the accessible rough-hewn rock components were "talking stones" or "seeing stones", a few selected structures had very special functions.

There are those archaic plazas, from which and to which megaliths point. These centres, these foci of radiating megalithic lines, are indeed special. It was there that geomancers became astromancers. Built on natural sites where black radiant energy discharges into and from space, these were the stations where eidetic information was intercepted among the worlds. In these centres, during certain seasons, ancient astromancers, literally "star seers" (astro-mantis) received steady receptions of exceptional conscious states...among the worlds. Black radiant energy surged, vigorously inflecting the consciousness of sensitives whenever special stellar-planetary configurations conjoined in the night skies. These were the

events which they collated and observed with religious devotion. Why such a motivated zeal? For the acquisition of new consciousness, new power over the elements.

Later, in architectural marvels of stone and geometric proportion, the black radiance carried strongly permeating eidetic information into recipients who were ritualistically more prepared. Stone-frames discharged the eidetic information in solar and lunar energies with great power in the dolmens. Clustres of stars and planets did so with rare delicacy. Those who have stated that megalithic structures are calendars and astronomical observatories know nothing of the mindraising energy. Theirs is an academic concern, which necessarily attempts the invasion of every unknown with the "known dogmatic". The ancients were not concerned with clocking and charting the skies for the abstract quest. If no experience was to be had, no communion with the skies, then the ancients would have abandoned the pursuit altogether.

Tribal energies were never wasted for excessive religious concerns. Those who seem to have done so were the members of societies in the decadent phase; desperately attempting to recapture their own lost mindraising technology by "appeasing" their false gods. While the more overt **astromantic** aspects of these mounds have been studied for centuries, few have comprehended the purpose for these mysteries. The space-effected modifications always produced specially prized mindstates and awarenesses. The eidetic visions which were associated with these receptions were the prized artifacts of an emerging priestly caste. Space-derived eidetic images were the "tokens" taken from the experience. These are portrayed in palaeozoic art expressions, and are most always misunderstood by those who examine them with academic preconceptions. Eidetic messages between ground and space. Information exchange between other worlds. These themes are not new among the archetypes within which we respond.

Without an experiential knowledge of these energies, one cannot comprehend the function of any ancient artifact. In fact, one cannot comprehend the modern expressions of technology apart from these black radiant principles, the very purpose and function of the VRIL COMPENDIUM itself. We each respond to every inflection and surge in the Vril Matrix. It is the connective environment and communicative envelope in which we move and have our being. Our own inflections of Vril, when life-affirming, effect a spreading impulse throughout the Matrix from which all can benefit. Negative inflections reside entirely within the confluent inertial space. We are each necessarily interpenetrated by these discharges, the external sustenance of our being.

The discovery of Vril in each society is attended by sudden and explosive growths in consciousness. The conscious magnification due to these developments produces Vril Technology. Each society produces its own peculiar blend of components and systems, whose first function is to maintain the new conscious state. This requires a technological system which becomes fixed, to some degree, through municipal mandate. Protecting the Vril Technology becomes the first action of any threatened society.

More advanced Vril-oriented societies developed systems which were self-protective. Of these, we must speak later. Most cultural groups rarely reached those levels of perfection. Recognizing that Vril Technology was the real core of their own survival, most ancient societies surrounded their Vril Systems with rich traditions and priesthoods. One would imagine that any society which discovers Vril and its wondrous consciousness-magnifying attributes would closely guard its secrets with such infallible safety measures.

11.3 VRIL TEMPLATES

Vril permutes, surmounting its previous states with unexpected new manifestations. Each successive Vril permutation contains within itself all the previous developmental aspects in amalgamated form. The process is one which spans the aeons. It is impossible to pierce this history beyond a certain range, the messages becoming too vast for mere human conscious ability to comprehend. Nevertheless, of the range which can be reached, we discover remarkable facts. First, each Vril permutation is intimately linked with the appearance of NEW ELEMENTS. Specific elements have been equated with Vril Templates throughout history. The memory and awareness of these epochal changes is preserved in mythology and the "Golden Age" or the We learn of this prehistory through examination of each element with an eidetic sensitivity. The development of special radionic instruments has permitted such eidetic examinations of elements.

Vril Archaeozoic permutations produced certain fundamental worldstates, materialized stages of development. Each such stage has been elsewhere referred to as a VRIL TEMPLATE. Vril Templates remain fixed, throughout the time that Vril is achieving its own intent. Templates permit the progressive development of new and unexpected technologies in which Vril currents alone are the dynamic agents. When Vril permutes, Templates change. Each Vril Template is a world state in which all previous Vril dynamics are incorporated and potentially active. These previous stages, these Templates, are represented today...in the ninety two natural material elements. Generating and surmounting the archetypes which it had previously projected, Vril develops and permutes into ever more articulate states. Each stage in its development produces a special and legendary VRIL TECHNOLOGY. Vril stimulates the development of technologies which enable humanity to powerfully appropriate its presence and providential supply. The implementation of the ninety two natural elements forms the basis of every Vril technology.

The evocation of a new Vril Template can be achieved through special technological means. These events occur when an intended climax has been wrought by Vril agents. It is then that we observe historical revolutions in archane science. During these times, some once impossible feats become possible. Archival study reveals a chronicle of discoveries having to do with Vril which is historically interrupted on several counts. Human history is a tragic panoply of both natural and human frailties, set on a broken stage. Disturbing is the interruption brought about by our world-condition. The natural enemies of storm,

flood, and other disasters are the horrid foes with which cultivated societies have to deal. But those enemies, born of human folly...of fire and sword, deceit, betrayal, suppression, rage, jealous greed, and ignorance...especially of ignorance, these were the most disturbing and lamentable causes by which glorious and legendary societies lost their place in the Vril Community. Such acts of pure self-destruction, all because of the desire for absolute rule, were seen all too often as the reason why societies lost their unique Vril Technologies.

Yet, of these obvious interruptions, the earnest student noticed another species; whose broken trail leads from ancient times well into the Twentieth Century. Unlike the first sad varieties, this interrupted path had a wondrous and graduated nature. In its ever-opening wake we find all the hallmarks of Vril itself. This strange terraced path, linking Megalithic Technologies with Radionics, is one whose developments surmount each previous technological species by astounding and unexpected expansions. It is indeed curious that the archane technologies gave sufficient wondrous performance to produce enduring mythical themes. The technological ruling forms and functions reveal that Vril existed in a form which is relatively differentiated as compared with its subsequent manifestations through history. Dare we say that Vril, in its manner of organic growth, progresses from original states to ever more highly developed ones? The expansive nature of each Vril manifestation reveals this remarkable phenomenon.

The permutation of Vril Technologies requires a primary permutation in Vril itself. One charts the surprising modifications in Vril Technology in sudden, complete leaps. This saccadic pattern is repeated throughout human history. One traces its flowering path, one whose blossoming development comes in ever new species. Thus, we date the appearance of each Vril technological stage. Natural Vril technologies begin with the isolation of groundpoints, trees, valleys, caverns, pools, ridges; all termed sacred. Next, we watch the development of human organizations: of priesthoods and devotions to the places known as sacred. After this phase, one discovers the development of special ornamentations in such locales. These humanly crafted artifices were added to sacred grounds specifically to magnify the Vril presence, securing for the tribal group an enduring access to magnified consciousness and its revelatory power.

Next comes the phase in which royal edicts enunciate regional establishment of Vril systems. Here we see grand public works, involving the entire culture in Vril directives. Next comes the supreme moment when such a society becomes unified in Vril Culture, the potential for unlimited conscious growth being delivered in floods. We will not account for the often subsequent degenerate phase, which appears to test the Vril favored society, a possible tragic decline and dissolution. Throughout this flow of developments, each society is imbued with a singular Vril state. This state, while being recapitulated through the centuries, permutes into newer manifestations. Boulders, tooled rock, covered rock...temples, altars, oracles...cathedrals, reliquaries, fonts...ground rods, variable capacitors,

inductors...the Vril functions remain the same, while being magnified in degree of endowed power with each such change.

Archetypes are not the portable, autonomic engrams of genetic inheritance as some narrators have insisted. Archetypes are external and independent. They invade the blank receptacle of mind, being messaged into human experience as Vril currents. Black radiant Vril space, their external generator, develops living eidetic imagery throughout the aeons. What it projects, becomes. Vril currents supply the archetypes which psychologists chart and which mythologies preserve. Rich in imagery, impression, instruction, and revelation, first Vril receptions are almost certainly those which encourage the establishment of Vril Technology. Imaginal floods permeate the recipient of Vril currents in cohesive, orderly sequences which suggest instruction. When this step is actively engaged, societies manifest sudden revolutions in consciousness. That which is called "civilization" is generated and supported by Vril currents.

First Vril receptions simply re-establish detailed articulations of lost world-Vril conditions; world-states which previous and forgotten societies had lost. Those who are thus raised in awareness begin realizing new enlarged worldvision; by which it is possible to make seemingly outlandish declarations concerning world reality. The personal communion with the black radiance being the means through which to gain heightened mindstates without negative effects, such statements are nevertheless made with absolute conviction. The absolute conviction of which we read in ancient writings on the world-structure.

Civilization collapses when Vril technology is abandoned. The decadent society is one which devalues and derides traditionally established Vril Technology. Lost sensitivity to Vril eidetic imagery places emphasis on purely inertialistic technologies.To delve into the true mysteries of radioelectric communications, we must first comprehend its intimate interactions with the Vril Domain. The search for some relevant technological starting point in these regards produced an epiphany in thought, typical for Vril investigations. Seeking technologies in which Vril was deliberately employed, one surely discovers a general and continuous sweep of developments. But, examinations of the specific nature of Vril Technological advancements presents the skillful bibliomancer with a true and wonderful conundrum which few ever address.

As centuries brought with them the accumulated forgetfulness, by which our race is usually accursed, all these wonders were lost. Vril does not cease in its continuity however, projecting and permuting the worldstate. New awareness of the interactions between matter and the Vril conscious continuum began again to influence human consciousness in the Seventeenth Century. The form of these new awakenings no longer required the massive stonework of Templar directed masons. In the experiments of Luigi Galvani, Maximilian von Hel, and Franz Anton Mesmer we see the emergence of a new Vril Template, a Vril Permutation in which the use of metals and articulate metal components first

manifested. Galvani, Von Hel, and Mesmer independently corroborated the fact that the energetic emanations from metals were capable of producing strong visceral responses. They each discovered the vitalizing interactions which occur between metals and human physiology. Maximilian von Hel performed experiments with specially shaped magnets and metal forms. These were placed in contact with parts of the body which seemed infirm. The result of these contacts was an amazing alleviation of symptoms in many cases where only pain and continuous debilitation was the normal progress.

Hearing of these developments, Franz Anton Mesmer sought a deeper understanding of metals and their role in such healing process. He wished to discover the "vis medicatrix", the energy of healing, with an aim to devise some accumulator of this healing power. Notable ancient European sacred spots became the site of fashionable spas and resorts for the rich nobility. Healing virtues often emerged directly from certain boulders and other stone columns. Over the centuries, sensitives had ornamented these with artistic additions. Boulders had become altars, columns had become pillars. Touch was all that was necessary in alleviating or even curing the infirm. There was much more to these sacred spots than legend and tradition. Recognizing that a real energy was responsible for these cures, Mesmer observed the geological structure inherent in most spas, seeking some means to imitate nature.

Mesmer developed his "bacquet", a grounded battery whose moistened multilayers of iron slag and organic matter (seeds, leaves, moss, peat) in such an attempt. This barrel shaped composite pile was fitted with a single iron pole which ran throughout the internal layers to the ground. On first trial, the design did nothing. Mesmer abandoned his barrel shaped design to the natural forces. This natural exposure brought a change to the apparatus through the course of time. The bottom rotting through, layers were now spilling slightly into the ground itself. Contact was thus secured with the ground directly. The layers had become soaked through summer rains. It was then that a new manifestation made itself known. Approaching the barrel, one sensed an uplifting force, one in which the entire torso responded. Touching the pole brought a strong body-coursing tingle, a thrill shock of great strength. Sleep or even blackouts were the result of such contact.

Later sensitive examination revealed a black radiance suffusing the immediate barrel surroundings. Mesmer discovered that remarkable responses surpassed the merely physiological effects in those who touched the pole. Passing out in a light dreamy sleep, persons who contacted his bacquet were frequently healed of lifelong emotional traumas. Later academic disapproval accused Mesmer of hypnotism, the commonly known "suggestion method" of cure. The association of the hypnotic method and Mesmer were the result of an early campaign to discredit the emerging Radionic Science, whose stupendous efficacies were threatening the financial base of medical practitioners. Other such campaigns reduced the Mesmer bacquet to electrical stimulation. Such a multilayered assembly of organic matter and

metal slag could never have produced any appreciable electrical current, especially since the whole was effectively shunted by the iron pole.

Independent experimentation with apparatus empirically found to permeate and beneficially modify human physiology, proved that a new technology was emerging (V.8.9). Galvani was first to postulate that metals emanated a powerful and permeating natural radiance. Galvani was persistent in his assertions that metals were surrounded and suffused by an "atmosphere" of emanations, an invisible light which flowed from them eternally. For Galvani, metals did not have to be in contact with physiologies in order to affect modifications. For Galvani, the invisible currents were capable of connectively transacting directly with physiology...at a distance. Galvani discovered that connections made between aerial metal plates and metal plates submerged in stone wells produced powerful "thrilling shocks" during fair weather. These arrangements released hazardous and potentially lethal shocks when the weather turned foul. His distinction between these two energetic species was never appreciated by those who followed Volta and his development of chemical batteries. Galvani made careful examinations of metals and their atmospheres, their auras, noticing the projective quality of copper, zinc, and iron.

Held close to the body, these most certainly produce responses well before actual contact is made. In this anomalous effect, one which cannot be adequately explained through aeric ionization effects, we perceive the legendary "Galvanic Current". Later academic reductions dared to suggest that Galvanic currents, radionic in nature, were simple electrical currents. Their reductionistic campaign came as a result of bureaucratic displeasure and an inability to resolve the natural phenomena which seemed so totally irreducible. Science was thus split into the two camps of qualitative and quantitative analysis, a schism which eventually resulted in mutual exclusivism. Nevertheless, the Qualitative Radionic Science emerged as the shadowy and elusive science to which military officials often resort when desiring outlandish technological effects. The absolute rulership of all inertial dynamics under Radionic Power is well known by those who implement its methods in secrecy.

Verifying the thesis of Galvani, von Hel, and Mesmer, Baron Karl von Reichenbach later observed the spontaneous luminescence of all matter in specially designed darkrooms. In this, he found proof that the projective emanations of metals successfully discharged through space in a continual flow. He named this luminous aura "Od light". The Baron conducted a great number of experiments with the "Od light", an emanation which he prematurely imagined to be the fundamental world force. He successfully directed this energy into wires, coils, and other laboratory apparatus used in electrical research. He absorbed Od light into metal plates from sunlight, moonlight, planetary light, and starlight. Thus absorbed, he discovered the conductive properties of this lightform...along wires. He optically refracted, reflected, focussed, and projected Od light from metals, minerals, magnets, and large crystals. He successfully photographed these emissions and discovered that unknown

materials could be identified with chemical precision simply by measuring their luminous discharge points along an Od conductive wire.

11.4 VRIL AND ELECTRICITY

The young Sir William Crookes studied the voluminous "Od Experiments" of Reichenbach with greatest fascination. He was especially fond of those investigations by which the Baron engaged vacuums and magnets or magnets a large crystals. When placed in belljars and gradually evacuated, the Baron observed the greatly expanded luminescence of each. The Baron also described the long-lingering effects of electrostatic shock on wires. Though grounded and completely discharged, these wires continued to flimmer with a wonderful white flimmering glow for hours. Sir William designed very high vacuum globes, poising various kinds of materials within their interiors in order to observe these spontaneous luminous displays. He learned that materials, when exposed to electrostatic discharges, continued to discharge their luminosity for hours. Deactivating these, he watched as the glow of diamond, ruby, fluorite, and all the other minerals continued to flimmer and sparkle for hours after electrical exposure. For Sir William Crookes, the phenomenon of electroluminescence was a means for magnifying the Od energy, formerly observed and described by Baron Karl von Reichenbach.

Electrostatic discharge also revealed a remarkable group of phenomena when both vacua and voltages were extremely high. At a certain point, Sir William could observe that the luminous discharge of the cathode departed from the cathode, leaving a black radiant space. It was in this black space that Crookes began realizing that a space suffusing entity was actually permeating the glass walls of his globes and pressing the discharge away from the bombardment source. It was in connection with this "black space" that he made extensive investigations. In this space he found a powerful momentum, capable of spinning radiometer vanes. No current was measured through the globes when this occurred, only a fixed high voltage. The inference was that this space suffusing entity was so rare that glass remained transparent to its presence. The mysterious space entity was motivated by electrical fields of intense strength, moving through the globes from space to cathode, cathode to anode, and anode to space again.

Observing the thready nature of discharges which flimmered through the globes among the electrodes, he imagined at first that this was a space suffusing gas. At first not recognizing the fixed and patternate articulation of these discharges, he postulated that they were the result of a rare gas, an "aether" which filled all space. Sir William eventually recognized in the dark space far more than a gaseous entity. He also recognized that his attentions were powerfully drawn into the space because of a more noumenous presence. In this black radiant space Sir William perceived something of the nature of de-inertialized space, a region where pure consciousness freely flowed. He continued these investigations along more spiritualistic lines of research, modifying the globes with concave mirrors and using

them to "scope space" for ghostly ectoplasms. In a number of wonderful portraits, he is shown holding various forms of this globular scrying device, peering into them at various angles.

Other researchers employed vacuum globes and connected them to ground directly. Using nothing more than a few variable capacitors, it was possible to receive eidetic currents of a powerfully magnified variety. These currents flowed through the globes, radiating from their free terminals. These came in sharp intermittent impulses, having specific duration. Tapping the eidetic contents of the Vril Matrix directly realizes long lost secrets of the archane technology. Finding continuity between the black radiant space of Crookes, and the spontaneous black radiant energy seen in nature, certain researchers have plunged into research on the fundamental nature of space and mind.

The true work and discoveries made by Nikola Tesla are yet not comprehended by those who claim to be radio engineers. One researcher alone stands paramount in the re-discovery of Tesla Technology. This work is based on findings made by Eric Dollard, a brilliant researcher, inventor, experimenter, and discoverer in his own right. What Mr. Dollard found in Tesla's patents and articles should have reported like cannon shots across the radio-engineering world. Reproducing the experimental arrangements precisely as Tesla prescribed, Mr. Dollard has discovered a true marvel in forgotten technology. The mystery concerning Teslian Radio centers around a singular discovery which Tesla made purely by accident.

In the Christmas season of 1891, Nikola Tesla made an accidental discovery which forever changed the nature of his research. Long associated with alternating current and alternating current devices, his complete rejection of these methods marked the change by which also his technology was later distinguished. While again attempting the duplication of experiments performed by Hertz (1887), Tesla accidentally discovered how to produce ELECTRIC RAYS. The distinct differences between Rays and Waves stimulated Tesla to recognize the long lost discovery of Joseph Henry, who first observed them. Henry accidentally released these Rays when conducting experiments with Leyden Jar discharges (1842). Through a bizarre arrangement of circuit parameters, Henry accidentally found it possible to magnetize steel needles several floors away from the apparatus. The duplication of these effects were accidentally arranged by Elihu Thomson in 1872.

Electric Rays had completely unexpected characteristics, being potent and piercing. Through them Tesla felt body shocks, though removed from his apparatus by several feet. He described the pressure effects of these rays in his conspicuously ignored paper of 1892 (Electrical Experimenter). In terms which most electrical engineers of the Victorian Epoch would understand, Tesla discovered the existence of what he termed "electrical soundwaves", or electrostatic longitudinal waves. In the generation, radiation, and reception of these special rayic energies, we find all of Tesla's statements and claims conforming to a new and unsuspected reality. Tesla's vision enveloped a glorious reality, flooding over with promise and potential. The

expansions of his primary discovery would have ruled the technological world.

Tesla drew attention to the fact that these energetic emissions passed through metal shields with ease. These Rays were powerful, while waves were weak. Tesla realized why Henry and Thomson had produced Electrical Rays and not Waves. He also understood why Hertz had only produced Electric Waves. The answer lay in the circuit parameters. Very strict relationships were required in the Ray-releasing process, relationships which few observed. So great was his excitement over the find and its potential applications, he accepted the otherwise untimely invitation of the Royal Society within the same year.

The energetic products of his Transformers were never duplicated by other designers. Even with regards to his smaller models, experimenters of the day failed to recognize the essential difference between magnetic induction and Tesla electrostatic induction. The two are completely dissimilar processes, producing completely dissimilar results. Tesla extended his discovery of the ray energy spectrum. Distinct from those of longitudinal light spectra, these lightforms represented an unknown energetic region. Identifying his rays as a form of "dark light", he developed new systems for their powerful projection. Every phenomenon which Tesla described differed so radically from those obtained by conventional methods. Researchers who worked with electric waves never observed the Teslian phenomena. Tesla always drew allusion to the fact that these electric rays interacted with the natural environment in an uncharacteristic manner. They seemed to self-intensify with progressive distance, a feat deemed impossible in the academic account of world phenomena. Nevertheless, Tesla measured a strange consistency which his projected electric rays maintained when passing through space. Though aerial in their passage through the environment, these effects were in all ways similar to those observed when telegraphic signals were applied to the ground (V.2.V.8).

Except we recognize that electrical applications and ground-injected signals stimulate a far more fundamental and non-electrical agency, we cannot comprehend or rationalize the numerous anomalies which appeared throughout communications history. The discoveries which Tesla made in relation with aerial electric rays constitutes a new chapter in the realization that a COMMUNICATIONS MEDIUM suffuses experiential space. Tesla and others at first imagined that an ultragaseous atmosphere, the Aether, suffused space. Tesla imagined that the aetherial gas was the source of all the energetic rejuvenations in his electrical ray experiments.

The supposed aether was also imagined capable of maintaining its momentum long after sufficient energetic impulse was delivered to it. Electrical rays were seen as a perfect means for achieving this interaction, one whose interactive strength was necessarily weak. Nevertheless, researchers employed electrical fields and electrical stimulations in attempts to move the aether. Being a theoretical gas produced by stellar crucibles, it was then proposed that the aetherial atmosphere itself might be

an available pressure tank of immense power. When once properly directed, an electrically stimulated aether gas flow could continue mounting pressure strength until some enormous maximum was reached. At this point, such an aetheric pressure stream could become the working fluid of a frighteningly potent generator...an energy source of eternal and enormous output.

The fact that this medium was not a gas came through a series of experiments coinciding more or less exactly with the discovery of X-Rays. When we look into the textbooks, the all too numerous investigations of cathode rays and their ancillary phenomena each seem mutually unrelated. Considering the time which lies between ourselves and these experimenters, our contemporary assessments often lack the necessary conceptual integrity required to recognize each logical step. The work performed with modified high vacuum discharge tubes revealed that cathode rays were possessed of a rayic nature, formerly equated only with light beams. The ability of cathode rays to preserve and project **images** of target objects stimulated considerable interest. While these cathode ray image shadows were observed entirely within the confines of the discharge tubes experimenters wished to discover if such projections could be maintained **outside** the tube.

The lightlike nature of cathode rays being in question, Tesla utilized the discharge tubes which Lenard perfected, Tubes which projected cathode rays into the air through a thin aluminum window were perfected by Lenard in 1894. In this research, Tesla was attempting to show that aether streams maintained the integrity of light, a feat otherwise impossible with elemental gases. Proposing of course that aetheric streams consisted of ultimately indivisible particles, an ultragas of incredible attributes, Tesla believed that these streams should maintain the integrity necessary for projecting **whole images** to greater distances without distortion. His aim was the development of television projection systems, utilizing the externalized cathode ray streams in an exact analogy to an ordinary magic lantern slide projector. With his own specially modified breed of Lenard tubes, Tesla discovered that it was possible to project image shadows of external targets through many hundreds of feet. In addition, Tesla observed that these rays penetrated through matter. It was possible for him to inspect skeletal structures and material interiors through several hundred feet. The use of phosphorescent screens, developed for his television system, enabled Tesla to first publish his findings.

Tesla later modified this system to be used in long distance ranging and detection. Having discovered the means whereby these very special rays could be produced, Tesla found it possible to develop streams which could be reflected from metals. It is in this experimental description that we realize what Tesla meant when referring to his research on X-Rays and, later, Cosmic Rays. Tesla asserted that very special radiations are aetheric streams, the absorption of which produced progressively larger particulate sequences. These differed with target materials, becoming the dangerously massive varieties being reported in certain European research laboratories. When honors for discovery of X-Rays was

bestowed upon Roentgen, Tesla observed striking differences between his own findings and those reported by the so-called discoverer. His own shadowgraphs did not require targets at all, being released by targetless high vacuum tubes. Powered by his own high voltage impulse currents, Tesla found that such streams completely altered the state of metals externally distributed and distant from the tube.

Tesla was always one experimenter whose refined investigations always permitted him a detailed understanding of natural phenomena. Whenever examining phenomena he explored every facet critical to the division of attributes which might harbor hidden conjugate energies, an aspect curiously absent in the process of modern researchers. The curious conjugate nature of his very special radiations with other anomalous energies became a singular feature with which he had become accustomed. Tesla found that he was able to duplicate the X-Rays of Roentgen only by adding metal targets within his tubes. Increasing the target dimensions of surface area and thickness was matched only by varying the target metals. In this way Tesla obtained a host of conventional X-Rays, the very first spectrum obtained in the study. This is why he forever maintained that his own radiant streams were "very special radiations". Indeed they were. When the discussion of whether X-Rays could charge metals came into question, commercially refined X-Ray tubes could in no way charge metals. Attempts at polarizing these rays through externally applied electrical fields failed with the heavier X-Ray species. Nevertheless, Tesla reported that emanations from highly electrified tubes of equally high vacuum could sufficiently charge metals to the sparking point.

Tesla expected that ray-projected images could be directed into the eyes, been seen through contact. His theory included the notion that the retina was an electrical terminal of great articulate detail. He thought that if the rays could be carefully chosen, they might reach the range of visible sight. Requiring special impulse frequencies as well as special tubes, Tesla engaged the search with enthusiasm. But the aetheric streams proceeding from these special tubes, contrary to his original supposition, did not convey images at all. In fact they were found to have no such ability, producing only a grey and leaden sleep, a state not at all like that expected. The later horror of reading Tesla's accounts concerning his exposure to such very special radiations has a curious aspect. His detailed reports in these regards filled the academic journals of the day, being adequate resources from which to draw new information.

His exposure to these beams is followed by accounts in which Tesla describes the sensations produced by "looking into the tube". An "internal racket" with "successive shocks in the eye" being reported, Tesla felt no other ill effects from his rays. The effects of these very special radiations on Tesla seem not at all similar to those one would expect were they composed of ordinary X-Rays, being inconsistent with the excessive age to which Tesla reached. While this practice is to be absolutely avoided, the tubes of Tesla were obviously also very special in their character.

In later years, Dr. Thomas H. Moray developed discharge tubes which had similar vitalizing properties. Although their secret remains well concealed, it has been reported that exposure to the flesh-permeating pink light results in vital states not unlike those associated with vitamin injections. The light actually appears right through the hand, and exhibits curative properties. It is not possible to achieve these results with ordinary discharges, a fact corroborated by both Tesla and Moray. Deep insight being required to produce such radiant emissions, the ability of most experimenters of the century's turn did not succeed in duplicating Teslian "very special" radiances. These energetic emissions, most certainly having the attributes of light, were claimed to yield excessively clear images. A gaseous stream of aether would necessarily give better definition than ordinary light, being theoretically more refined than light. This was the working hypothesis on which Tesla based his original television system.

It was known that the retina could be rendered phosphorescent, a condition observed with the production of special ultraviolet apparatus. Tesla did not find in these very special radiations a means for conveying imagery directly into the retina. Working with the idea that such streams did cause phosphorescence in mineral-coated screens, it was difficult to imagine why a simple adjustment of the streams themselves would not effect a similar phosphorescence in the retinal surface directly. The streams caused a noticeable eradication of light and visual sense, not an intensification or increased resolution of imagery as he supposed. For a while, Tesla was baffled with the puzzle before him. But it was not in relationship with these energetic electrically stimulated streams that Tesla realized his most exceptional discovery in these regards.

11.5 VRIL AND GEOELECTRICITY

From the first days when researchers drove rods of copper, zinc, or iron into the ground there have been strange effects noted in electrical systems. In an earlier time frame, such locations were identified by sensitives and geomancers. Once termed as sacred spots, the impatience of the emerging communications industry brushed past all the ancient sensitivities with characteristic brusque disapproval. Nevertheless, these sites became the contemporary origin of numerous paranormal occurrences. Dowsers were employed by the Western Union Telegraph System to locate "good ground". These locations defied theoretical concepts of battery action, often not being found where they "should be": near lakes, swamps, and streams. Examination of the depth in which the groundplates were buried did not adequately prove the role of ground water or water table in the phenomenon.

These points of "good ground" were known to be perfect for the placement of telegraph terminal groundplates. Buried in these locations, telegraph systems were endowed with enormous "electrical" results. These points released prodigious amounts of an electrical current into the telegraph station. Being unidirectional in nature, the power was used by frugal stations

owners to operate their lines for decades...without batteries. These powerpoints could not be predicted by theoretical analysis. They could not be found, the result of any grid system. One had need of employing natural sensitives for the location of such groundpoints. Their location often required great skill and patience, the focal diameter often being less than a yard. It is yet possible to find such points with a carbon rod probe.

Carbon, inert when used in halide solution batteries, acts as a powerful receiving material for ground energies. Conducted during winter, one finds the persistence of ground currents despite the hard frozen grounds. A iron rod is driven into the ice-hard ground and connected to a sensitive galvanometer. The other terminal is connected to the inert carbon rod. Probing the earth with the carbon rod, the experimenter finds with amazement electrical registrations which can be identified in very precise groundpoints. Dramatic electrical rise can often be found to within a diameter of one inch when passing across the ground surface. These electrical touchpoints grow in power with time, disappearing completely when the rods are withdrawn for an instant. One perceives that the energy which is drawn up to the ground surface can also quickly withdraw. In this, we recognize bioresponsive dynamics. The astute and sensitive investigator will often find that the currents flood over in eidetic discharges, being the literal exchange of eidetic messages between trees and other vegetation (Lawrence).

While developing systems for transmitting electrical power through the ground, Tesla discovered that rapid electrostatic impulses effectively cohered natural dielectricity. It was thus possible for him to apply small increments of electrostatic power, and receive vastly magnified results. He gradually learned that specific impulse vibrations produced larger resultant effects. This amplification or "magnification effect" was known before Tesla began experimenting with its properties, although its proclamation was not overtly shared among academicians. It was known by telegraphers, whose application of short battery impulses through the grounded lines resulted in sustained states of electrification. It was possible to continue signalling without batteries in these states for hours. Incapable of explaining the phenomena, most engineers sought cause within the internal systems in which such magnification effects were manifesting.

Tesla's first experiments with the magnification effect were conducted in his New York laboratory before 1895. Tesla had long observed thunderstorm activities and imagined harnessing the true source of their fury. Fueled by this enormous source, the world would be liberated from its dependence on fuels. Observations and measurements made in New York enabled the determination of impulse parameters required to "prime" the dielectric potential. Tesla envisioned an upwelling dielectric flow which would require very little prompting once initiated. His "spark start" method employed very powerful impulses of specific duration. Once delivered to the ground, the dielectric current would focus into his system, upwelling in an ever-magnifying flow which could be tapped for industrial use. Once the continuous flow was obtained,

Tesla foresaw only the need for maintaining and regulating the flow. No further energy applications were ever necessitated after the initial impulses created the "spring".

With this futuristic goal in sight, Nikola Tesla designed and operated the very first earth-influencing VLF and ELF systems in New York City. The devices were moderate, but decisive in effect. He needed larger structures in order to gain the industrial scale power required to defeat the fuel monopoly which Morgan had organized. When news of his research leaked to certain individuals, certain acts of desperation were undertaken. Morgan had long demanded entry into the conglomerate which both Tesla and Westinghouse owned outright. When Morgan threatened reprisals, Tesla politely warned him that technology could answer for its own defense. Morgan organized two independent monopolies in order to dominate the AC Industry. One such front was the domination of fuel. The other was the domination of every relevant industry for the production of AC powerlines. Morgan returned with his reply, stating that AC generators and appliances would be useless without the means for conveying the power to consumers. Tesla replied by developing means for transmitting power through the ground. Thus eliminating the need for powerlines at all, Morgan was thunderstruck.

This direct collision Morgan resulted in an assassination attempt, from which Tesla very narrowly escaped. His fortunate absence from the laboratory that evening, a variable which his enemies had not anticipated, alone allowed his survival. The complete destruction of the famed laboratory by fire (March 13, 1895) marked a radical change in his approach to the socially elite. Morgan, thunderstruck that he survived at all, weakly responded to Tesla with a small endowment for the reestablishment of his laboratory. Tesla played the game to the hilt, publically requesting a larger sum for his newest venture. Morgan was pressed into the grant. Having plans of returning to New York with a piercing technological reply for his smug financial antagonists. Tesla moved his experimental researches to Colorado.

Very specific ground placement and equally specific impulse power were the two requirements for cohering the voluminous geoelectrical energy which he anticipated. His gigantic Experimental Station rose on a mountain plateau. The structure housed a Tesla Electrostatic Transformer of huge dimensions. Being nearly eighty feet in diameter, the device was constructed with several functions in mind. First, the necessary application of a very specific pulsating current would be arranged. Tesla wished to sparkstart the geoelectric reservoir for an instant. The resultant continuous discharge could be withdrawn for a very long time thereafter. The brief application of this initiating power required a receptive apparatus to engage the upwelling resultant energies. Tesla designed a special interior coil which was to become saturated in the upwelling energy. It was with this coil that the geoelectric discharge could be modified and rebroadcast through the ground. Tesla arranged so that the broadcast energy would not interfere with the initiatory pulsations. Changing the pulsation rate of this broadcast current enabled the broadcast of electrical power to consumers

everywhere. Photographs taken in Colorado evidence the continuous discharge of energies from the huge Magnifying Transmitter after an extremely brief power application has been withdrawn. The impulses obtained from the single switch closure resulted in an energetic torrent lasting several minutes.

Most believe that Tesla systems were designed to broadcast electrical charges. Tesla systems were designed to transmit and receive **dielectric energy**, a current not well understood by most. The associate charges which appeared around the station were the annoying by-products which Tesla continually sought to eradicate. The Magnifying Transmitter of Tesla employed IMPULSE and not alternation. The operation of this device depended upon the application of electrostatic impulses, not harmonic alternations, directly into the ground. The anomalous characteristics of these impulses have never been adequately assessed. It is probable that these impulses, being dielectric currents, were not reflected when passing through the ground. Their application was not therefore one in which a return impulse, other than the geoelectric response, would be accommodated. Influencing the development of electronic charges throughout the ground however, charges would become hazardously concentrated with progressive impulse applications. The accumulated charges represented energies lost to the natural environment, requiring constant dissipation. This is the second function of his elevated capacity structures. Their first function was the aerial transmission of dielectric rays to drive aerostats, planes, the levitating craft to which Tesla made constant allusion, ships, trains, trolleys, cars, industrial power needs, and ordinary household requirements.

Thus drawn from the geoelectric reserve, Tesla would provide free power to the world. This unexpected technological development signified the complete closing of a chapter in human history: the demise of fossil fuel as the driving force behind industry for all time. The demise of fossil fuel suppliers. This second reply to Morgan vibrated the very financial core of the world. In this single demonstration, Tesla moved the world system on many fronts, a lever of unsurpassed power. First the wireless transmission of power, now the fuelless production of power. Tesla wished to suborn and control the ruthless Morgan so that his technology would not be annihilated by financial means. By inviting his principle antagonist into the new technology, Morgan himself would back the effort. Offering him first financial rights, Tesla again publically applied to Morgan for funds to develop a World Broadcast System. Morgan again was forced to respond.

Tesla also observed that specific points especially responded to the initiatory electric impulse of his Magnifier. Other spots in the vicinity sprouted electrical discharges while his station was operating. These impulse having been delivered, it was evident that a group of previously unsuspected natural geoelectric vents were discharging simultaneously. In speaking of this phenomena, Nikola Tesla announced his discovery of "stationary waves". Often confused with more conventional "standing waves", the Teslian phenomenon of "stationary waves" is

completely different in nature. Representing a constant efflux of electrostatic energy from a fixed site, the "stationary waves" varied in their manifestation from ground point to point.

The basic attributes of these spots did not always include visible spark discharges. Those aspects having to do with the presence of charge were also not always present in these places. What was always present consisted of a dielectric field whose values aperiodically rose to tremendous strengths and fell to normal values. Tesla identified a pulsating nature in the geoelectric emissions of these fixed stations. They emitted sudden, often violent bursts of geoelectricity often evidencing very high vibratory conditions. These energetic effluxes rose in amplitude with an aperiodicity related to distant lightning storms. Tesla realized that as dielectric lines processed up through these groundpoints, electrostatic charges were being developed in situ. Other points register reverse current production, indicating that dielectric discharges are entering the ground from space. But what made the dielectric currents flow in these fixed points at all? What influencing feature maintained these places as geoelectric vents?

The discovery of both stationary waves and geoelectric vents made his system a practical reality. Tesla postulated that such points were natural vents for the discharge of excess storm currents, natural vents for geoelectric reserve. These points maintained the "geoelectric pressure" in natural environment. Application of dielectric fields to his transformer coils always resulted in a conveyance of energy, energy which manufactured electrical charge as an "in situ" by-product.

Recalling the early accounts of dowsers and telegraphers, the renewed awareness of these groundpoints and their significance was not at all surprising. They nevertheless captured the world ear by storm. It was recalled that these points were often found near wooded areas, even as Stubblefield had noted early in 1872. The activity of these points was never diminished by the frozen ground of winter, an impossibility for the electrolytic model. These electroactive groundpoints were taken by Stubblefield to be spontaneous discharge points, not operating by conventional electrochemical models. Furthermore the energy drawn from these points were obviously direct currents, driving the telegrapher's responder with force. Stubblefield used them to light arclamps, heat his cabin, drive motors, and power wireless radio telephones. Stubblefield suspected that these geoelectric direct currents were possessed of a vibrant nature. He found it possible to transform these currents through successive coils.

It is also noteworthy that Stubblefield did not require the gigantic structures constructed by Tesla to achieve his results (V.7). A simple multilayer coil was buried at the roots of oak trees. Stubblefield noted that the weak electrolytic currents were gradually augmented by the appearance of currents "having commercial value". Tesla corroborated the existence of these loci, and measured their vibrating outputs with accurate instruments. Some spots were found to be more energetic in their geoelectric output than others. This was thought due to

geologically related factors. When geologists were later sent out in search of the active or "good grounds", neither electrical measuring devices nor geological survey map could predict their location. This truth was as baffling as the manifestation itself. If no geological pattern could be discerned among these geoelectric points, what indeed caused the activity? Not every ore body released geoelectric phenomena, nor did every watery ground.

The identification of such stationary wave-release points represents much more than an untapped natural resource capable of eradicating the fuel cartels. Being natural wells where a host of conjugate energies simultaneously appear, these points represent a means by which world-wide communications can be achieved in way never before dreamed. While most were thoroughly entrenched in electrical methodologies, the most fundamental manifestation of these loci were being discovered by a small group of independent medical researchers. The resultant science of RADIONICS prove that the permeating effects of a highly organized and patternate nature actually rule all inertial forces and their processes.

11.6 NATURAL ELF

It is difficult to discuss radioelectric VLF and ELF without a necessary survey of infrasound and its associated phenomena. Infrasonic components are generated in the environment through the application of ELF outputs. Radioelectric VLF and ELF stimulate massive vibrations through the tensions, torques, and stresses which they induce in the inertial component of matter. Large massive objects respond with powerful vibrations when conducting natural ELF. Large sections of the terrestrial ground measurable vibrate during episodes when geoelectric ELF surges are released. While geoelectric and solar electric ELF stimulate a variety of effects, their primary force seems to produce two major components.

The energetic complex formed by natural ELF energies in the physical environment is a biohazardous combination of radioelectric ELF and infrasound. Objects vibrate until the shattering point during certain ELF episodes. Not much ELF amplitude is required to produce such infrasonic material stresses. Not much ELF Complex amplitude is required to produce physiological malady. Several researchers accidentally did themselves great harm when, by deliberate intent or accident, they succeeded in generating ELF vibrations. Tesla used vibrating platforms as an aid to vitality. He delighted in "toning the body" with vibrational platforms of his own design. Mounted on heavy rubber pads, these platforms were vibrated by simple motorized "eccentric" wheels. Their mild use, for a minute, could be pleasantly stimulating. The effects invigorated the whole body for hours thereafter. Excessive use would produce grave illness however, excessive aggravations of the heart being the most dangerous aspect of the vibrant stimulation. The entire body "rang" for hours with an elevated heart rate and greatly stimulated blood pressure. The effects could be deadly.

In one historic instance, Samuel Clemens, Tesla's close friend, refused to descend from the vibrating platform. Tesla was

sorry he had allowed him to mount it. After repeated warnings, Tesla's concern was drowned out by both the vibrating machine and Clemens' jubilant exaltations and praises. Several more seconds and Clemens nearly soiled his white suit. The effects of infrasonic vibration on the human body was then "duly recorded". Tesla often went to great lengths in describing the effects of infrasounds to newspaper reporters who, behind his back, scoffed at the notion that a "little sound" could effect such devastations. Yet, it was precisely with such a "little sound" that Tesla nearly brought down his laboratory on Houston Street. His compact infrasonic impulsers were terribly efficient. Tesla later designed and tested infrasonic impulse weapons capable of wrecking buildings and whole cities on command.

It is not coincidental that Tesla investigated the related effects of ELF radioimpulses and sonic impulses. Radioelectric impulses often produces sound. Take for example the loud humming sounds which appliances often emit. Loose coils and other components often radiate sixty-cycle AC tones of a remarkable penetrating nature. But there are natural instances in which both ELF radiopulsations and their related complex of infrasounds occur. Barometric variations, registered in the acoustic ELF range precede earthquakes. The power of these pulsations is enormous, measured both in barometers and in electrometers simultaneously. But there are instances in which no seismographic registration corresponds to the enormous barometric fluctuations. Such mysterious and sudden barometric variations indicate that natural infrasonic generation has a much wider source than the subterranean earth.

Space projects groundward ELF Complexes with enormous proficiency. The years 1840 through 1890 were absolutely unprecedented in the numbers and intensities of such auroral storms. Auroras were seen at atypical locations in the daylight. A special group of observers were established to monitor these auroral and other cataclysmic conditions in the environment. The Carnegie Institute was one such laboratory where a host of environmental observations were made on a continual basis. The mood of the times warranted this world "watch", the general impression being that a world shaking event was about to be unleashed. Victorian investigators observed the erratic rotations of compass needles during each auroral episode. These compass signatures signalled the arrival of an auroral episode in a few hours.

Comprehending the nearly instantaneous magnetic registration as a result of connective field currents, Tesla wrote extensively on the topic. With respect to the associate and conjugate appearance of ELF Complexes during the terrestrial reception of solar flares, there exist a primary and immediate manifestation with which Tesla was most aware. The reception of dielectric currents occurs with the very onset of solar flares, being connected directly with the ground. Specific locations seem especially receptive of solar emissions. Other locations, defined points in the topography, seem especially receptive of other astromantic projections. It was in these regards that he developed systems for interplanetary communications. His systems

involved the use of dielectric currents, not particles.

In more terrestrial applications, the auroras exhibited deleterious effects on communications and other electrotechnology. Telegraphic stations experienced astounding hazardous electrifications during this time, operators having been killed by the room-long discharges which crackled out of telegraph keys (V.2). During these episodes, telegraphers abandoned their terminals altogether. Others used the auroral inductions to operate their systems. This was especially true of the trans-Atlantic cable systems. In some cases, operators placed the hazardous receiving wire in their mouths, receiving transmitted impulses by auroral charge (V.1). Electrical powerlines were burned out by excessive amperages induced by sudden auroral maxima.

ELF Complexes associated with the Aurora Borealis are too numerous to mention, a well chronicled occurrence. The aurora borealis is heard to "swish, crackle, sizzle, and...thunder". Quantitative analysts cannot understand how these sounds can be "heard" but not recorded. It is obvious that certain auroral sounds stimulate neurophonic responses (V.5). Such neurophonic responses never register in biologically unmodified electronic systems (Lawrence). Though academic debates continue over the ability of some persons to hear higher auroral tones, the deep "thunder" of the aurora stimulates certain ELF Complexes which can be measured. Low level auroras have been actually seen and felt. The sounds and odors associated with this rare phenomenon are unmistakable (Corliss). In one instance a chemist was fortunate enough to have lived, after witnessing the effect of auroral grounding throughout his laboratory. The incredible luminescence produced in several platinocyanides, electro-phosphorescent chemicals, were duly noted and reported.

In another rare incident the literal "grounding of the aurora" into an elevated radio tower was observed by a number of astounded witnesses. The on-duty radio engineer of the station suddenly heard a crackling sound which came "from everywhere". Unable to transmit any signal power, the radiosystem failed completely. Meanwhile, he felt completely electrified and smelled ozone everywhere. Not realizing what was happening all around him, he believed that the transmitter had somehow gone awry. Hearing and feeling a deep humming sound aroused fear. Numerous witnesses who saw the event, describing the colored column of light which suffused the tower, feared he might have been killed by its frightening permeations.

The auroral high pitched "sizzling" and "swishing" sounds are augmented by deep and ominous thrumming. The ELF combination of electrical and acoustic pulsations, deep and frighteningly powerful tones, sweep through the bodies of listeners who are fortunate enough to survive the dangerous encounter. These permeations produce an irritability and a dizzying nausea. The sounds associated with these electrifications were always equated with evil by the Eskimaux. Their legends of the aurora are always fear-filled. The trademark of anxiety and dread highly characteristic of ELF energies, their tales also recount the "taking" of souls by the "ground walking" aurora. Numerous

observers have reported that the aurora actually "swept along the ground" like a column descending from the sky, taking a multicolored appearance all along its meandering path. Others have watched the aurora descend and remain hovering over a meadow. Yet others have observed such auroras touch ground, and take on an uncharacteristic green coloration, spraying bright drops of light all around the column (Corliss).

Blasting through interplanetary space, solar flares assault the earth with an aperiodic barrage of stupendous proportion. Their disturbing effect on electrical systems is historically noted. The terrestrial effects of such sudden pulsations in outer space has resulted in large scale power outages, the amperage induced in powerlines and steel pipelines reaching dangerously extreme levels. Some 139 solar flares were recorded between 1980 and 1983. There is a statistical 155 day periodicity in solar flares, a rhythm often violated by several interstitial flares. Principally used for predicting their expectable effect on radio communications, specific military observers monitor solar flares with continued concern. The appearance of electrical power surges during solar flare events has amounted to many hundreds or even thousands of amperes line-induced current. Northern lands design their power systems to accommodate these periodic manifestations of great power. Oil lines in northern lands must be carefully grounded and insulated to prevent the continuous induction of such harmful electrical surges. Standing arcs of brilliant blue current have been observed upon the surface of loose pipe joints during solar flares and strong auroral episodes.

Travelling at thousands of miles per hour and charged to enormous potentials, flare pressures aperiodically barrage the neutral atmosphere. These violent dielectric currents do not stop at the atmospheric blanket. The explosive influence of vast electrostatic power shocks the entire weather system through the very ground (Jacobs, Patel, Cahill). Electrically active flare disturbances violently disrupt all atmospheric processes. The very obvious outlines of flare contacts with the atmosphere can be traced as major pressure changes on weather maps. Solar flare impacts strike the earth like a bell. Auroras result, and have been correlated with thunderstorm activities (V.1). When the surging electrostatic flux from each gust enters physiology, the penetrating consequences seriously modify health on a worldwide scale. Flares are the extremes of the solar influence. Some have cited correlations between flares and earthquakes. Others have cited evidence that flares stimulate viral epidemics.

Besides the extreme impulses of flares, the continual minor background solar disruptions produce a steady barrage which cannot be discounted. In its normal process, solar expulsions do not arrive at the atmospheric boundaries as a homogeneous pressure wave. The arrival of solar products comes as a pressure wave of inconsistent density. Expelled from the solar surface in blasts, the vacuum of space does not appreciably alter the space-launched bursts. These particulate bursts arrive in the terrestrial reach within a day. This intermittent barrage induces harmonic atmospheric disturbances which continually modify and chaoticize emerging weather patterns. The effect is exactly like

"thrumming" an evenly sanded drumhead with innumerable impacts. This imprint of "background" pressure waves, rattling daily upon the atmosphere from solar winds, can be seen as "Chladni" patterns on weather maps and in cloud forms.

In these patterns, constantly evidenced throughout auroral and atmospheric activities, we glimpse the true causative agency responsible for stimulating all of these manifestations. Wherever biohazardous inertial states are encountered, there we will see evidence that black radiant Vril is performing its antagonistic functions. In a manner which is totally biological in response, Vril threads actively dissolve inertial concentrations. When this occurs, we observe "natural electric and magnetic displays". The patternate core of these displays is not the result of inertial response. It is the result of a Vril action on inertial space. Inertial response is characteristically chaotic, incapable of producing, sustaining, or conveying any organization. Black radiant Vril manifests itself throughout all these phenomena, being the generator of organization.

Both solar flares and the normal thrummings of the solar wind exhibit a combined electrostatic and infrasonic pulsation throughout the atmosphere. The ELF and infrasonic shockwaves from the aurora are normally not heard, but definitely sensed. Measurements have registered a continual infrasonic background noise level. This pressure energy emanates "from above" atmospheric strata, radiating downward in large patterns. Atmospheric ELF Complexes are most strongly measured during daytime hours, a clear indication of their source in the intermittent expulsions of solar wind. Atmospheric ELF Complexes arrive at measuring stations with pitch between .67 and 1.5 cycles per second. Their pitch continuously oscillates between .67 and .83 cycles per second. These pressure waves are powerful and massive, like waves of the ocean in which one is helpless. These solar sourced infrasonic impacts very definitely correlate with sudden swings in human behavior, having very obvious sociological implications.

In the minds of investigators such as Tesla and Keeley, the energetic content of atmospheric ELF represented a vast and untapped potential. Buried steel spheres and their thin copper tubes successfully produced barometric pressures capable of raising massive objects. Thomas Edison and others demonstrated the use of such sound in driving wheels (V.3).Few writers have discussed the intermittent effects of solar flares on atmospheric pressure. The sudden changes noted in air pressure, which cover many thousands of square miles, are obviously sourced in the solar wind. The effect of this natural radio ELF assault on the atmosphere produces disturbing influence on both the weather and human behavioral patterns. Correlations of flares with jet stream behavior is strong. Jet stream behavior, in its meanderings and undulations across vast geographic regions, is not mysterious when considering the intermittent effect of solar flares and the normal "background" bursting of the solar wind.

Natural phenomena are prodigious generators of ELF Complexes. ELF Complexes move, unaffected, through and across both winds and storms. Some individuals can hear the jetstream

and its thunderous pitch, peaking between 30 and 40 cycles per second. More and more populations are reporting the persistence of ultralow pitch sounds which render them weak and fatigued. Having often unexplained sources, we find the bibliography flooded with cases of persistent "atmospheric...and underground sounds". Natural ELF and its associated infrasound complex is inaudible to human hearing, being of pitch below 15 cycles per second. ELF Complexes are not heard, they are felt. They hold a terrible secret in their silent roar, producing varied physiological sensations which begin as vague "irritations". At certain pitch, ELF Complexes produces painful physical pressures. Even at low intensity, they induce fear and disorientation. At very specific pitch, they can incapacitate and kill. At others, ELF Complexes can explode matter.

Predators utilize the ground-hugging property of very low and ultra-low pitch sounds. Surrounding the herds of animals on which they prey, predators maintain constant communications through their low pitch tones. There are in fact grounded locations into which very low pitched actually funnel. These fixed locations focus very low pitch tones which are generated elsewhere in the environment. This phenomenon has gendered numerous biotoxic conditions which have been reported throughout history. In attempting the more conventional explanation of these dynamics, some theorists claim that wind enters caverns, producing an immense artificial whistle of infrasonic resonant pitch. Careful examinations of these caverns reveals infrasonic pitch of 20 to 30 cycles per second which does not "register" on tape recordings. Some have suggested that these focalized ELF Complexes (the Taos Hum) are only sensed in the sensitive tissues of bioorganisms. But investigators have found that ELF Complexes actively seek and focus into specific groundpoints.

ELF Complexes travel long distances, often exceeding one thousand miles with virtually no attenuation. The pressures represented in these complexes arrive at great distances with the same force and intensity as when released. The atmosphere sustains prolonged and powerful infrasonic vibrations. When Krakatoa was violently ejected away from the terrestrial envelope, windows shattered a thousand or more miles away. Seismographs and barometers rang for hours after the event. ELF Complexes hug the ground. Were it not for the numerous Vril dissolution orifices which cover the ground, ELF Complexes would not cease in their harmonic oscillations across the world surface. Being rapidly absorbed and metabolized into these mysterious groundpoints, the dangerous energies are diminished with a rapidity which perplexes theoreticians (Taylor, Sao).

This corroboration of much earlier discoveries in geoelectricity stimulated interest in the more ancient recognition of these very same sites. It is not coincidence that many of the emerging radiotelegraph and radiotelephone stations were constructed on such old sites, openly bearing their names. Theoreticians propose that the incidence of ground-focussing ELF Complexes is an "electrostatic" manifestation, the result of emerging terrestrial charges in small terrestrial foci. Stubblefield recognized these points and used their output to

advantage. Tesla rediscovered them and demonstrated the ability to cause them to spill out usable power with uncharacteristic force. We are not at all surprised that ELF Complexes funnel down into such natural sinkholes. These are not physically spacious openings or caverns. They are solid groundpoints. What then is the reason for their ground saturating response? Vril actively dissolves inertial manifestations. In the behavior of ELF Complexes we are observing an aggressive metabolic response within the Vril Matrix for the complete eradication of the biotoxic densifications.

Earthquake related ELF Complexes manifest only at intermittent intervals, producing drastic and sustained negative modifications of consciousness (Finkelstein, Powell). These complex vibrations contain geoelectric, geomagnetic, and infrasonic components. The human organism continues to reel under their intermittent infrasonic assault. After less than a five minute exposure to low intensity earthquake related ELF Complexes (10 cycles per second) dizziness lasts for hours. ELF Complexes of 12 cycles per second produce severe and long lasting nausea after a brief low intensity exposure. The extreme irritability of ELF Complexes victims has been noted in numerous earthquake events. The harmfully stimulating influence of ELF Complexes renders physiology permeable and ultrasensitive to every available environmental sensation. The body becomes literally overstimulated to the point of complete auto-destruction. The effects greatly exceed those noted with mere infrasonic impacts. This is because, in addition to the more overt pressure effects of ELF and its associate infrasonic components, there are the more penetrating and truly biotoxic neuroelectric effects.

Striking similarities have been noted between the periodicity of natural magneto-dielectric pulsations and the vibrant form of brainwaves. Evidence exists for correlating the weak entrainment of brainwave rhythms under solar flare impacts (Konig, Hamer). Numerous individuals have reported feeling a sudden and unexpected nausea, a weakness and trembling having short flu-like symptoms. Greatly exceeding the arrival of the particle bursts, these subjective experiences correlate with the very instant in which solar flares have been observed (Ormenyi, Menzel, Salisbury). Violent flare pulsations reach disturbing neuroaffective crescendi. Solar activity, though normally too weak to influence human and animal behavior, does reach entrainment intensities during certain peak flare emissions. The behavior of all bioorganisms in varied natural events (thunderstorms, tornadoes, earthquakes, volcanic upheavals) all relates to the manner in which neurology is modified by ELF energy complexes (Chapman, Mathews, Konig, Reiter, Aarons, Henissart).

ELF cannot remain isolated as a radioelectric identity when once introduced to the terrestrial massive environment. The inertial aspect associated with matter is directly influenced by ELF, forcing its strains and torques, tensions, and stresses on all matter which contains inertial percentages. How such naturally extant conditions can systematically modify individual human behavior for protracted seasonal periods is frightening.

How such natural conditions can systematically modify wide and unified social behavior for protracted seasonal periods is more frightening. Those researchers who imagine that a merely infrasonic pressure influence on human physiology is responsible for al the observed physiological effects are not entirely correct. ELF energy necessarily produces its energetic complex of associated vibrations in material transducers. If the responses of human and animal recipients is not acceptable to quantitative analysts, then there are other means to prove the hazardous effects of natural ELF on bioorganisms. ELF vibrations are inertial and suborn all matter, the forced vibrations having been monitored in a great variety of inert instruments.

Not much power is required for naturally occurring ELF Complexes to produce such extreme and sustained physiological symptoms (Reiter). Infrasound merely impacts the outer body. It produces its neurodepressive effects by mere induction, a crude process by which vibratory pressures produce biotoxic neuroresponses. The most potent and experience-penetrating effects are produced by ground conducted ELF. The infrasonic components surreptitiously induced by ELF, is not the penetrating bioeffective signal. The electrovibratory inductions of ELF couple directly with neurophysiology. Ground emerging ELF vibrations enter specific neurological pathways and entrain behavior. Naturally occurring ELF entrains alpha waves, at 10 cps and delta waves between 3 cps and 5 cps (Konig, Hamer, Rowland). Physiology remains paralyzed by short exposure to ELF Complexes (Herin). Physiology rages antagonistically after such biohazardous exposures, Vril fighting to maintain bioorganismic equilibrium. ELF Complexes stimulate middle ear disruptions, ruining organismic equilibrium. The effect is like severe and prolonged seasickness. ELF Complexes immobilize their victims. Restoration to normal vitality requires several hours, or even days. Exposure to mild ELF intensities produces illness, but increased intensities result in death.

It is very evident that inertial impressments can influence behavior by distorting visceral responses and conscious perceptions. Devices which achieve these objectives, infernal machines, succeed only in so enraging Vril that it responds with violent antagonism on behalf of bioorganisms to destroy the irritant. Anomalies observed at military ELF stations should sufficiently warn their operators of an impending personal doom. Alarming responses to ELF Complexes have been accurately recorded by military medical experts. Scholars do not speculate on the aggressive pursuit of these studies throughout the twenty years following World War II. Participants have never come forward to protest the abuse which followed commanded consent. The American military tests have a more deadly design. The effects of ELF Complexes on servicemen were examined in lengthy research programs. ELF Complexes in the range of 40 to 100 cps. were engaged by unfortunate volunteers. Military examiners recorded sobering responses to these minor energetic applications in young servicemen.

Decreased infrasonic pitch greatly raised the deadly symptoms. Great power was not the decisive factor. Pitch was the

deadly force. When we read that military projects have been designed to peak at megawatts levels, we should be horrified. Covering these investigations with characteristic panache, the military claimed that such knowledge was vital to comprehending the performance of jet plane pilots. It is clear that these were weapons research programs. The deployment of such energies would produce symptoms no different than the release of nerve gas.

Careful examination of the data indicates that violent physiological and neurological reactions follow insignificant exposures to both VLF and ELF (Konig). In addition, the liquid crystals in body tissues receive and amplify ELF, modifying all neuronal processes (Parker, Carr, Picardi, Russo, Caldwell, Tasaki, Chang). Such ELF triggered modifications are stored in restructured physiochemical form. Altered cardiac rhythms, with pulse rates rising to 40 percent of their rest values, are the precursors to other pre-lethal states (Reiter, Teng, Howard, Brezowsky). Cardiac and other neurofunctions are entrained and driven by the external ELF source (Tromp, Wever, Persinger). Mild nausea, giddiness, skin flushing, and body tingling occur at 100 cycles per second. Vertigo, anxiety, hyperthyroidism, extreme fatigue, throat pressure, and respiratory dysfunction follows (Papp, Skeres, Tudhope, Frey, Goeke).

Visceral microvibrations begin at 12 cps and persist down to 4 cps (Tiscenko, Rohracher). Coughing, severe sternal pressure, choking, excessive salivation, extreme swallowing pains, inability to breathe, headache, and abdominal pain is observed between 60 and 73 cps (Lotmar, Altmann, Weise). Cardiovascular arrhythmia develops in long term ELF exposure (Papp, Skeres). Fibrillation and embolism, with ELF modulated VLF (Halse, Quennet, Kummel). Blood flocculation, sedimentation, and coagulation, in VLF ranges of 10,000 cps (Takata, Tromp, Eichmeier, Ruger). Body piercing arthritic pains precede last stages before total anaesthesia and death, each of which occur in succession with prolonged ELF exposure (Ludwig, Mecke). Long after their irritating presence has ceased, physiological reaction to ELF Complexes remains. Post exposure fatigue is marked. Certain subjects continue to cough and vomit for half an hour, while many continue the skin-flush manifestation for up to four hours. Increased body weight and edema is a physiological response to mild ELF exposure (Persinger, Glavin, Ossenkopp).

There are more shocking physiological results which occur in the lower ELF pitch range. Significant visual acuity decrements are noted when humans are exposed to ELF Complexes between 43 cps and 73 cps. Failure in judging time occurs at 10 cps (Hamer, Wever, Poppel, Giedke). Intelligibility scores for persons exposed, fall to a low of 77 percent their normal scores. Spatial orientation becomes completely distorted through inductions in the hippocampus (Orme, Crosby, Humphreys, Lauer). Muscular coordination and equilibrium falter considerably. Learning and memory disabilities are induced at 0.01 cps and 1.0 cps (La Forge, Rowland). Loss of attention, decreased attention span occur between 4 cps and 7 cps, the theta waves (Gavalas, Walter, Hamer, Ady). Depressed manual dexterity, reaction times, and slurred speech precede complete anaesthesia. Electronarcosis

actually occurs with exposure to 0.1 cps (Becker), although at stronger signal levels in the VLF band (10,000 cps) electroanaesthesia also occurs (Photiades, Riggs, Aiyvorh, Reynolds).

Dr. Vladimir Gavreau explored the infrasonic range between 1 and 10 cycles per second. His team found that lethal infrasonic pitch lies in the 7 cycle range. In this pitch range, small amplitude increases affect human behavior directly. Intellectual activity is first inhibited, blocked, and then destroyed. As the amplitude is increased, several disconcerting responses had been noted. These responses begin as complete neurological interference. The action of the medulla is physiologically blocked, its autonomic functions cease. The process is painful. A painful death.

11.7 VRIL AND RADIOELECTRIC SYSTEMS

In our previous discussions, we have seen that the mysterious Vril Matrix exists in distinctly organized strata. Suffusing the physical ground, this stratum generates and sustains bioorganismic and conscious continuity. Early aerial radio influenced Vril strata in the deeper ground, producing notable eidetic transactions. Because of this ground densified passage, VLF transmissions manifested a marked geodirectionality. Despite these anomalous and paranormal manifestations, the longterm results of such energetic applications were always deleterious. Controlling district integrity in fundamental eidetic parameters, the subterranean Vril Stratum began accumulating and maintaining biohazardous states. Later aerial radio produced its stronger modifications on the overlying Vril strata in which bioorganisms had their principle habitation.

When radioelectric current is applied to the ground, Vril becomes enraged and overwhelming in its response. Necessary for the maintenance of bioorganismic integrity, eidetic currents must never be irritated by any external means. We recall that double ground electrical systems grip the Vril stratum which underlies districts. Applying powerful irritations directly into this densified stratum of currents, entire regions of ground become dangerously overactive and over inertialized. Applications of electrical irritants cause eidetic currents to shift from insensate states to sensate states. This conversion process results in a derangement in the normal inertial dissolving process, with unusual perceptual distortions the result.

Throughout the early Twentieth Century, inventors sought methods and means for generating either alternations, oscillations, or unidirectional impulses specifically for radio communications systems. In each such patent we find the repetitive, plagiaristic trail which leads directly back to its source. Tesla had earliest patented all methods for mechanically and electrically generating all manner of high power electrical discharge; whether alternations, oscillations, or unidirectional. But Tesla employed only his own special unidirectional currents of high voltage dielectricity in the operation of these designs, a principle which seemed to elude the very best inventive minds of the day. The first designs which Tesla revealed did not and

could not utilize electron currents. They utilized dielectric currents, and have remained the bafflement of all electrical engineers to this date.

Various VLF and ELF generating systems were developed by other designers after Tesla, systems which never equalled or duplicated results actually obtained by Tesla. The patents of Fritz Lowenstein, an assistant to Tesla, offer us serious insight into the secret work of Tesla himself. They are obvious misappropriations of Teslian developments. They indicate the Lowenstein himself did not grasp the most basic intentions of Tesla. Intent on achieving or surpassing Tesla, each designer strove along with Hertzian waves, using Tesla now-abandoned high frequency alternators to achieve their bombastic goals. Valdemar Poulsen produced very large versions of the original Tesla magnetic interrupter for use in Hertzian wave transmitters. These mammoth installations provided power for a host of improper applications. Marconi, insisting on the use of Hertzian waves for telecommunications, developed huge aerial radiosystems which employed Poulsen Arc generators. Throughout these years, Tesla's work was copied and adapted to the wasteful wave transmitters. Tesla never required such energetic applications, patiently describing the high efficiency of carefully designed impulse circuits.

The progressive movement of radio, from subterranean to aerial Vril strata, effected strong changes on consciousness directly. Modifications in the Vril strata which lie above ground effect specific kinds of modulations in the auric environment. These energies, being conducted through the aerial Vril stratum, affect all bioorganisms directly through the aura. When aerial radio shifted into shortwave energies, the most inaccessible aerial Vril strata were directly engaged. Touched by these inertial shortwave streams, the upper Vril Stratum responded with a downpour of highly collimated spacic Vril discharges. Normally discharged from astromantic sources into fixed groundpoints, raybeam and wavebeam radiosystems helped rediscover what ancient astromancers had always known: columnar channels where space energies blend into the Vril matrix. Once so received into their groundpoints, these astromantic currents modify and alter consciousness directly through auric connection.

The antagonistic interaction of Vril with electrical generators (electrical impulses, oscillations, and alternations) influences the performance of a system. Vril seeks the eradication of all environmental irritants. Note the curious manner in which the very first huge installations were rapidly destroyed through both social or natural force. Vril antagonistically interacts with electrified systems in specific biological ways. Vril exhibits all the characteristics which is revealed in protoplasm: metabolism, assimilation, growth, catabolism, irritability, pleasure, reproduction. Double ground electrical radio systems are Vril irritaters, subject to dangerous metabolic consequences. Stations are literally "digested" over time, while Vril seeks the eradication of electrical systems. VLF transmissions travel through grounds, being focussed into intense power or defocussed into weaker

signal strength. Rejected, "marked", and "tracked" by Vril natural dynamics, Tesla was never able to comprehend the rapid manner in which each of his systems were being systematically eradicated.

Tremendous attention was given to infrasonics during the last war. Late in World War II, the Nazi army developed infrasonic devices of great destructive force. German infrasound weaponry used blank gun shells as a compressive source to feed ultralow pitch acoustic resonators. The sonic beam which emerged from this strange and deadly ultralow pitched gun had devastating effects on target herds of animals. EL audio energies travel along the ground surface, hugging and riding the topography to their targets as an ever-spreading wall. The total effects at a distance were empirically greater than the input energy. In horizon-level demonstrations, the French tests of infrasound devices produced uncommon manifestations of resultant power. Unbalanced input-output equations could not be theoretically accounted. These and other experimental results indicated to researchers that a "more than acoustic power" can suddenly be engaged; one which is enjoined by properly modulating and the natural Vril matrix. It was this imbalance of equation which triggered renewed investigation of the radio ELF effect. After the war, it was found that ELF Complexes are definitely sustained and amplified by a mysterious ground sourced energy stratum.

Taken again from accounts which Tesla reported, the role of infrasonics appears minuscule when compared with the more potent electrical energies from which they are produced. Engagement of the Vril ground matrix was accidentally stimulated through many different kinds of experimental apparatus. Sonic excitations of the ground are found to effect **geoelectric responses** when infrasound is employed. The weak mutual interaction produced measurable effects on unfortunate personnel. Vril antagonistic responses will pierce, cavitate, dissolve, and absorb inertial concentrations of all kinds. Whenever inertial space is thus aggressively assaulted by Vril, electrical effects are observed. This is how an acoustic process can result in the production of an electrical manifestations.

Tesla declared that ELF Complexes, produced by special peak pulse electrical generators, can be directed through thousands of subsurface miles to any target. Appearing most overtly as earthquake waves, the neuroelectric characteristics of these energies are devastating. Nothing escapes the permeating electric effects, irregardless of press releases to the contrary. During the International Geophysical Year, several new aspects of ionospheric characteristics were investigated with military objectives first in mind (Campbell). Recall that Tesla's radioelectric pulsations did not employ Lodge harmonic resonance, and were not therefore capable of stimulating Hertzian waves. Teslian impulse vibrations are unidirectional electrostatic components. They do not ride between ground-ionosphere waveguides. Tesla made these facts perfectly clear in his polemic on "The True Wireless" (V.9). While certain harmonic alternating currents result in the propagation of Hertzian wave energies, these do not permit the vast and continuous communications which

Tesla engaged. It was with very low transmitted power levels that Tesla was able to communicate effectively across very broad expanses.

No doubt military personnel seized the opportunity at this early date. Their interest in all such systems since World War I has not been covered. One finds numerous articles describing military funded beam weaponry during the 1920's (V.10). The new methodology which Tesla espoused seemingly permitted the creation of hideous long-range weaponry. What the designers of such systems did not anticipate was the more frightening and long lasting response of the Vril Matrix. While the Vril Matrix responds to all electrical irritants in a biological manner, it does so with special fury when specific pulsation rates are applied. This also relates to the stratum into which the irritants are applied. Though conducted for potentially longer distances without signal loss, ground conducted radiosignals do evidence more rapid signal demise than expected. In addition, these signal dissolutions occur in a patternate manner, suggesting a patternate dissolver.

Vril will destroy any radioelectric signal and its transmissive system. In the aerial Matrix, the applied beams and rays are dissolved more readily. It is in this regard that we observe the optical demise of signal strength with distances. Propagation studies reexamined the theoretical proposals which were consolidated by Austin early in the century. Originally observed by Marconi and Fessenden, the variable nature of Hertzian wave propagation in the terrestrial envelope provided a fascinating new awareness of world structure. Tesla never expressed these concerns, not utilizing Hertzian waves in his radiosignalling systems. Marconi was dependent on these studies however, the success of his already faltering system depending on propagation variables. These were observed by Fessenden, who remained concerned with the dramatic variation in signal strengths by the minute. Utilizing VLF Hertzian signal modes, these investigations failed to comprehend what Tesla had already stated. He stated that the use of Hertzian waves would be fraught with disappointments, being the heatlike detritus of the lossy harmonic alternations. Tesla espoused the much more efficient ray transmission system which did not suffer from any of these variables.

Early having observed that signals could not cross the Atlantic along east-west directions, a fact contradicted in the strong east-west Pacific transmissions, Marconi stationed his Atlantic transmitters along diagonal paths. It was also found that trans-Atlantic transmissions were strong along north-south lines, while the same directions produced weak receptions across the Pacific. The study spawned a great controversy on the nature of radio and its transitions when crossing land or sea. It had been gradually realized that the homogeneous propagation of radiosignals across the sea or uniform land was a myth. The were too numerous empirical discoveries of radio "blindspots", places where no amount of applied power could leak a signal into an area. On the contrary, excessively strong cóncentrations of radio signals were empirically found in other locations. As with early

telegraphers and their search for "good ground", no geological pattern could ever be found to explain these radio anomalies.

It was clear to military engineers that radiosignalling required a detailed knowledge of propagation constants. Only an exhaustive series of investigations could secure the knowledge which insured communications during any conditions. There were so many variables which had to be considered. Geoelectric and geomagnetic variables played a large part in the propagation of trans-oceanic signals. There were problems associated with static, and ionospheric conditions directly linked with solar illumination. Meteorology played the large part when certain radiofrequencies were employed. Military personnel needed to know when certain frequencies could not be used. They recalled what Tesla had said concerning his static-free receptions and ray transmitters. ELF variations were observed with location (Galejs, Sparrow, Ney, Ranscht), solar conditions (Menzel, Salisbury), season (Tromp, Konig, Holzer, Deal), weather (Konig, Ormenyi), and diurnal hour (Konig, Hughes, Theison, Reiter). Geomagnetic ELF disturbances were noted (Jacobs, Patel, Cahill), along with geoelectric ELF disturbances (Abbas, Poverlein). The obvious search for an unjammable communications system was but one of the many protocols. The results of this intense geophysical study produced a new regime of radio related military projects.

In weak attempts to rediscover Teslian objectives, several avenues of research examined natural electrical process in outer space. One group examined ionospheric phenomena. The others reexamined subterranean conduction phenomena. each group developed and deployed systems having undoubted military function. A series of radio studies were designed to study "Schumann resonance", the natural waveguide occurring between ground and ionosphere (Galejs, Saito). These studies revealed that VLF and ELF Hertzian waves could stimulate resonance in this ephemeral natural condition, producing extraordinary world-wide propagations. Numerous geophysical research projects heated the ionosphere directly above certain highpower UHF and microwave frequency radio telescopes. Born of this research, several projects effectively deployed geophysical effects which had been attempted with some success earlier in the century. Claiming to utilize theoretical analysis for the development of "infallible communications systems", one questions these research pursuits on a great number of items. The work of numerous military-compromised individuals in the United States has explored these methods. Motives which exceed the ordinary "protection of national borders" are obviously implied. What "national security" would demand the establishment of such systems within the national boundaries?

The work of Ulivi, Grindell-Matthews, Hettinger, and Reno with powerfully collimated beams demonstrated an ability to simultaneously activate the mysterious "geoelectric" ground points. Responding to the sudden application of aerial radioelectric irritations, these Vril centres forcibly dissolved the inertial concentrations. This resulted in a visible white interchange between the aerial electrifications and ground Vril. It was imagined that the electrical detritus, surrounding the

vertical Vril shafts, might be a possible new energy source (V.10). These systems were in several ways different from those which passively absorbed electrical charges from the air (V.1). They employed pulsations which stimulated far greater charge production. By employing specific pulsations, as Tesla outlined, they could literally force the geoelectric reservoir to vent through the surface. But power systems were not the end of these applications. Several military systems employed highly ionized atmospheric beams to form conductive channels for heavy pulsed currents. Aimed at aerial crafts, such beams were effective in both neutralizing engine operation and even destroying the craft altogether (V.10).

PROJECT WESTFORD was publically billed as a communications experiment. The evidence points to a military involvement, using an orbital swarm of independent copper wires as microwave "antennas". Released into orbit in the millions, this copper shredding formed the conductive sheath required to disrupt, rather than advance, communications. Supposedly the heart of a new space relay system, the exceedingly poor signal receptions were shown to a bewildered public in the mass media. Nevertheless, it is obvious that the scheme was designed to effect selective communications disruption. Radio telescopy beamed microwave "signals" at the orbital sheath, achieving its original objectives. With the development of orbital technologies, these outlandish schemes were withdrawn.

Only a casual perusal of the impulse generators, included in our modest collection, will convince that the military has continuously developed and improved VLF and ELF generators. Some of these are monstrous transformers, made to convert high amperage electronic currents into high voltage currents at ten alternations per second. Such powerful charges induce tremendous influences in geophysical strata. Using forgotten MHD systems where extremes of high power may be developed at these incredibly low oscillation realms, military systems can yield multi-megawatt alternations over a very large ground area. Poulsen Arcs were the apex of VLF and ELF Radio Science. His designs began in the work of Nikola Tesla, having been described by him in lectures made before the turn of the Century. Poulsen combined the use of hydrogen gas and magnetic flux to generate current disruptions of the heaviest sort. Hydrogen arcs providing extremely rapid pulsations, these designs were later reconfigured into Thyratrons and Gammatrons. The ultrahigh power radar systems of Dr. P.L. Kapitza (then USSR) produced over one gigawatt of pulsed peak power, being multicavity magnetrons of over one meter in diameter. Usable transverse RF energy was delivered along tight beams in attempts at duplicating the effects described by Tesla. This erroneous view indicated a total ignorance of Tesla's true discovery. Nevertheless, the Russian military yet commands tremendous radar power sources which can be utilized in any number of tactical applications. It is clear that, in addition to these huge radar systems, stupendous power potentials are available for delivering VLF and ELF pulsations to suitable aerial structures.

PROJECT SANGUINE, of dubious function, has been promoted as a submarine communications system throughout the publically accessible bibliography. Deeper still are those realizations by which we recognize the hallmarks of weaponry and deadly systemologies. SANGUINE is billed as a system which needs not operate at high power ratings in order to reach submerged submarines. Disseminators of such disinformation suggest that the biological effects of PROJECT SANGUINE are so minuscule at these insignificant power levels as to be ignored. The power ratings they test and base their statements upon are indeed less than ten watts. But this placation fails under closer scrutiny. SANGUINE is constructed to accommodate megawatt pulses. Military and Government-affiliated engineering researchers declare the regional effects which SANGUINE ELF alternations will produce when once the system reaches megawatt amplitudes is stupendous. What then is this but a military weapon system?

ELF spreads out as it propagates. In a military scenario, the projection of ELF Complexes from such an extensively deployed system would be strategically decisive. When once released into the environment, the focal center of ELF Complexes could never be localized or eradicated. There are now a great number of individual SANGUINE sites. Together, these produce the composite ELF signal. An obvious flaw in military public relations concerning PROJECT SANGUINE centers around the location of transformer antennas. One well might ask why a submarine communications system is ground-based so far inland. Might not a better conductive arrangement place the terminals directly in the available seacoasts? If seacoasts are considered vulnerable, then there are any number of coastal sites from which ELF energies might well be introduced directly into the open seas. All of these objections and suggestions would be important if SANGUINE were truly a submarine communications system. There being no military advantage to placing the transformer antennas inland, we must suspect that the project has nothing whatsoever to do with communications at all. Numerous military-funded investigations have more recently been compiled to study the effects of strong VLF and ELF radio impulses on human behavior. This is usually couched as "concern for the public welfare" or "submarine communications systems".

These weak smokescreens are incommensurate with various recovered patents in which we see military applications of ELF pulse technology clearly stating their objectives as both natural and behavior modification systems. If military reports make an opened show of concern for the "low level ELF" which could "leak into social sectors". Why then are these systems designed to accommodate megawatt peak-pulses? It is not by coincidence that the SANGUINE ELF radiosystem indeed influences physiological systems and entrains brain waves (Wever, Persinger). ELF entrains physiological and neurological process, driving the systems externally (Konig). ELF paralyze intra-physiological neurology, conditioning stimuli to await external driving impulses (Reille). SANGUINE effectively entrains the neurology of every living being in its worldwide range. SANGUINE is not a milliwatt ELF system, being structured to accomodate megawatt pulse potentials.

Parasympathetic and sympathetic nervous systems evidence specific sensitivity and response to externally applied ELF from 100 cps down to 1 cps (Ludwig, Mecke, Ranscht-Froemsdorff, Tromp). Organisms enter resonant entrainment with the operation of this system, circadian cycles being drawn into the SANGUINE resonance mode in a relatively short time period (Wever, Konig). During this time period, organisms experience a baffling nausea and malaise not unlike the response to solar flare emission previously mentioned. Strong neuralgia with partial paralysis and equally mysterious loss of sensation accompanies this initial response. Neurological disturbances accompany the operation of all grand scale ELF experiments. Once a population has entered entrained resonance with military ELF systems, all neurologies become compromised. The hapless victims of SANGUINE modulations follow the leader in each signal application. Pulsed at intended megawatt peaks, organismic neurologies would simply cease to function. Thus, the electrical system broadcasts the same effects as a nationwide dispersal of nerve gas. Sustained use of such a system would be effective in modifying the consciousness of any population. An ELF system would theoretically require not more than one watt to exchange signals across the world.

The continued effort to develop radioelectric weapons has brought forth a series of very obvious systems whose deployment in the public sector has been covered. Claiming these systems to be either "communications" or "ionospheric" research devices, one discovers quite the contrary in patents and technical articles on the same. Military and associated patronage being cited in each such publication, one peers through the printed matter, recognizing the potentials which lurk in such systems as SANGUINE and HAARP. Born of the aerial experiments conducted in the early Cold War Years, PROJECT HAARP was developed as a weapons system of frightful geoderanging potential.

HAARP manages the modification and modulation of ionospheric electrons to effect each of its several military objectives. Behavior modification seldom being mentioned, the more overt functions of HAARP are weather modifications, beam destruction of land through focussed solar radiations, neutralization of all electrical machinery, neutralization of all electronic communications systems. It would therefore seem that World Government, in the hands of multinationals, is preparing for a time where possible anarchy can be effectively and silently neutralized without traceable evidence of involvement. The net effect of radioelectric ELF is not simply to generate electrosonic pulsations in all free-standing objects. The various humming sounds which have been heard across the nation have their plausible origin with Projects such as SANGUINE and HAARP.

The entrainment of neuroelectric systems by natural ELF sources has been observed by several researchers (Persinger, Ludwig, Ossenkopp). It has been determined by a group of private observers that a complex network of military VLF and ELF broadcasts continually exchange information at very fundamental physioelectric levels. The "Russian Woodpecker" and other such ELF radiosignals have been recorded and monitored on a constant basis by private military observers. Findings indicate the

extreme psychoactivity of such signals, emanating from a single location in the Russian heartland. For reasons mentioned earlier, it is difficult to pinpoint this ELF transmitter site with accuracy. Experts have suggested that this system is a direct copy of the Tesla Magnifying Transmitter. If indeed a Magnifying Transmitter in form, there are serious doubts as to whether Russian engineers have arranged the proper operation of this pulsating system. It seems that the signals are Hertzian alternations. Others have suggested that this energetic and annoying raster is a pulsed radar communications device, compressing code into a slow pulsed radar transmitter. Compressed in each burst are contained enormous quantities of code and other directives. Such codes can be modified to "speak" directly into neurology. Neurophysiological activity occurs between 100 cps. and 100 cps., and from 1 cps. to 50 cps. in the brain (Persinger).

This transmission system is not the only one of its kind in the military world. The United States engages in similar transmissions, although obviously not localized in any single station. VLF and ELF Broadcasts come in the form of rapid bursts whose origins can be traced to several stationary sources, all of which evidence a complex switching. This VLF network uses multiple stations to transmit a single barrage of brain entraining messages. No one station carries all the information in the signal. Stations share each barrage. Each ELF barrage does not last more than a few seconds. These bioentraining energies do not require continual radiation for their continual effect. Neurological systems maintain the entrainment for hours, "ringing" to the entrainment as a unified whole. Military researchers succeeded developing and deploying several kinds of ELF modifiers of physiological and perceptual states. These employ biotoxic vibrations, having power in inertial space to bring ruinous effects on consciousness, conscious process, and geobiological integrity. Populations have been entrained by this means.

11.8 EIDETIC COMMUNICATIONS

Tesla had long discussed the therapeutic applications of electrotechnology with greatest enthusiasm, having described several different impulse systems which he himself employed to raise vitality. He planned to broadcast several such therapeutic applications on a worldwide basis. Along with the production of power, Tesla fully intended on broadcasting physiologically vitalizing and **mind-elevating impulses** throughout the world. His World System would effectively maintain public health through therapeutic broadcast energies, while **raising consciousness** into ever elevated states. This function of his Wardenclyffe Station was covert. Masked by his announcements concerning radio-telephonic exchange terminals and international communications, Tesla made allusion to the technological modification of "human energy". This aphorism was used elsewhere by Dr.Albert Abrams and other researchers to describe the energy of...the human aura. The principle focus of Tesla's research in electropulsation was to determine specific neuroelectric responses. This is evident in

his detailed descriptions of physiological effects at certain pulsation rates. raising the frequency of unidirectional impulses produced several successive experiences. Pain, heating, physiological repulsions and attractions were found to both appear and disappear with raised impulse frequency.

Tesla Electrostatic Transformers excite special impulse resonances in the ground, modes which differ completely in dynamic scope from those military ELF PROJECTS which excite harmonic ground oscillations and alternations. Tesla's devices raised consciousness. Military ELF depresses consciousness. And this occurs by deliberate design in certain operative modes. The Magnifying Transmitter of Tesla was never intended to harm social populations or derange social consciousness. When pressed into its use as a military weapon, Tesla saw fit to describe its possible use in debilitating armies at a distance. His announcements were always very carefully planned press releases. Along with his other descriptions of lethal rays, they coincided with the very outbreak of World War I. Tesla stated that triangulated Magnifier broadcasts from several fixed sites could bring enough neuro-effective pulsations to paralyze and even kill all opponents.

But there were other effects to which Tesla made allusion. Tesla made several comments on the operation of his device in Colorado which reveal truly anomalous effects long following its operation. In his diary, he made reference to some effects which have been curiously overlooked by scholars. Tesla was famous for the casual manner in which he reported exceptional phenomena. In Colorado, Tesla noted remarkable perceptual distortions which followed the engagement of his Magnifying Transmitter. After the **withdrawal** of all electrical energies, his Experimental Station became the scene of strange perceptual modifications, free standing ocular distortions, and noumenous projections. These included astounding intensifications of visual and audio clarity. He stated the ability to hear thunderclaps several hundred miles away. A phenomenon of visual tunneling, amounting to remote viewing was reported. He told of the ability to sight train wheels at ten miles' distance. Distortion of local perceptions was noted. Tesla told that a horse appeared to be gigantic, though moving along a road which ran at a few hundred feet distance.

Each of these effects occurred during the daytime...long after the Magnifier had been deactivated. The lingering results of this operation was not at all taken to be the result of continuous aetheric streams. In this report, Tesla also casually mentions the striking and noumenous presence of a suffusive and "inky black" radiance associated with moonlight. Tesla equated this inky blackness with the Crookes radiant dark space...an astounding equation, one which is not coincidental. Previously mentioned by Tesla in connection with small laboratory transmitter operations, he had once made reference to the fact that he could draw continuous amounts of energy long after his transmitters were deactivated. Operating various devices with energy from space, his consistent observation that long silvery white and clingy threads could be drawn from objects throughout a

demonstration space. This once convinced him that the continuous flowing energy was aetheric in nature, the result of electrostatic coherence in the aetheric atmosphere. But these perceptual distortions were not the result of aetheric streams.

If the optical and experiential distortions were the result of light, diffracted by dielectric distortions, they would never have been so prolonged in effect to continue into the daylight hours. Dielectric lines straighten themselves from any externally applied deformations at highest speeds. Though more highly defined than even the light particles, which he imagined to be the cause for visual continuity, Tesla could not account for these purely **eidetic effects**. He recalled the effect of his vacuum tubes on perception and their lingering after-effects throughout the space of his demonstration hall.

Recall what Tesla had discovered when experimenting with his vacuum projection tubes. Hoping to sight projected images directly, he succeeded only in being painfully occluded and barraged by inertial energies. The eidetic flow occurred for hours after the exposures, a time period during which Vril was repairing damage done to both Tesla and the environment through ray exposures. It was clear that the application of electrical energies brought only occlusions. The problem once again required new analysis. How to send images through space directly with electricity? The answers came from unexpected sources much later...without the use of electrical energy at all. Eidetic and inertial components remain separate, being mutually exclusive. Each realm produces experiential effects which are mutually antagonistic. While body permeating ELF signals interact with neurophysiology, they do not interact with the aura. Auric anatomy is not electric in nature, and does not partake of electrical interactions however permeating.

In all of this, later military analysts saw a powerful means for modifying the consciousness and physiological states of distant populations. In this phase of Tesla's work, government aligned researchers saw a new means for controlling behavior directly. The new study was named "psychotronics", one whose application had gained popularity throughout the period between the World Wars. It was seen by independent researchers that changes in the Vril Matrix could effect changes in the auric states of bioorganisms directly. Either through the air or into the ground, experiments in electrotechnology accidentally realized the new region-modifying technology by which defined changes in weather patterns could be effected (Tesla, Baigorri). It was also discovered by certain investigators that properly entuned ground-transmitting instruments could rid farmland of certain vermin (Hieronymus, Hughes, Grafe, Knuth). Working with those guidelines which Tesla outlined before the turn of the Century, certain researchers developed shortwave radioelectric devices which eradicated disease states and raised physiological vitality (D'Arsonval, Abrams, Lahovsky, Burwitch, Emerson, Arnold, Warburg, Colson, Miller, Knight, Caldwell, Bronson, Wigglesworth, Gallert, Hieronymus, Rife et.al.).

To those thoroughly entrenched in the electrical models, the notion of effecting any kind of regional change through "blank

tuning instruments" seemed fanciful. Nevertheless, several researchers realized that direct modifications in the Vril ground strata would transmit their message throughout a region with special permeative intensity without electrical applications (White, Drown). Tuning instruments were carefully designed, employing electrical components. When simply connected to ground, these non-electrified tuning instruments could influence vitality as if electrified. Recalling the first instance when such devices appeared in the Patent Registry (V.4. Edard, Hicks, Mellon, Ziegler), this reawakened interest in therapeutic ground energies marked the division between psychotronics and true RADIONICS. Radionists made tremendous discoveries with both grounded and aerial tuning instruments (Hieronymus). These systems seemed to be ineffective on first examination, being seemingly "nonpowered". Nevertheless, those who were exposed to emanations entuned from the ground quickly changed their opinions.

Radionists established a consortium, meeting in semi annual conventions with ever increasing numbers throughout the nation. By the end of World War II there were literally thousands of physicians and other medical practitioners who employed radionic methods in both their diagnostic and curative procedures. The systems demonstrated real and measurable effects. One could raise vitality by the turn of a control knob. The two principle components used to effect entunement of ground emergent energy included rheostats and variable capacitors (Abrams, Wigglesworth). Rheostatic components included nichrome wire (Abrams, Drown) or carbon band varieties (Hieronymus). Radionists experimented with the process of transferring vitality from ground to patient. It was found that specific refined tuning could restore health to the infirm. These principles were extended to the restoration of conscious states with surprising success. In many cases, patients who suffered from memory lapses and other neuroaffected symptoms were raised up from their low vitality into health by this method.

Others further extended the principle to a regional application of vitality. First attempts at raising soil fertility through radionic entunement alone were met with astounding and measurable success (White, Lahovsky, Hieronymus). One could theoretically raise consciousness by the application of specific RADIONIC PATTERNS throughout an entire region of ground. Connection with the Vril linkages, thready channels between regions, could transact the beneficial effects to other districts. How are these effects spread throughout the ground? What is this energy of the ground? How do simple "blank" tuning mechanisms effect any kind of vital transfer?

Whether in the ground, discharging across spaces, or traversing along conductive lines; Vril appears in instantaneous thready crystallizations. These thready crystallizations, of lengths determined both by the conductive system and the nature of the Vril procession, wriggle in a fluidic manner. Vril thread processions expand, contract, assimilate, grow, creep, multiply, bifurcate, automagnify, discharge, pulsate, and throb. Whenever and wherever ground connective Vril discharges are resisted or occluded in their path to bioconscious organisms, health and mind

are lost. This loss of unobstructed communications with the Vril Matrix can occur both in a personal and regional manner. Inertial space assaults and permeates the physical body, effectively fixing and rigidifying emotions and thoughts to specific crepusculated boundaries. It resists, occludes, blocks, distorts, and limits conscious reach. When possible, inertial space will also seep into a region of ground. Achieving this, inertial space then occludes bioconscious access to the Vril Matrix.

Bioconscious organisms require connective communications with the Vril threads which feed them. Vril threads feed us with a range of bioarticulate currents through which we have our being...our consciousness. Impacting the inertial component in matter or space, Vril reestablishes its connective communications with a region. Wherever it does so, Vril produces complexly woven patterns which are not unlike wood grains. Examined through conductive materials, these bioarticulate currents evidence a completely patternate character (Vassilatos). Organic patterns. The delicate response of material media determine the delicacy of these remarkable patterns. When properly channeled, such patterns may be viewed in human vocal utterances (Hughes). One recognizes, by examinations throughout nature, that these patterns are highly articulate. Vril is articulate, expressing its energies in eidetic images. Within the patterns flow the marvelous eidetic images by which Vril is known and distinguished.

These patterns represent the way in which inert matter responds to the passage of Vril currents. These patterns only evidence the more objective attributes of ground emerging Vril currents. One can entune different patterns through the selective Radionic process. A few radionists discovered that the patternate currents contained imagery...eidetic imagery. Exposure to these clarified images brought remarkable recoveries from illness, as if looking at the right image would restore lost health. These eidetic images were photographed and preserved on thousands of print papers (Drown, DeLaWarr). The conclusions which can be reached from this astounding science leads to the future, as it is derived directly from the forgotten past. In Radionics we see the reemergence of the lost archane science through which ancient societies became cultures, and cultures became civilizations.

Vril is organismically absorbed in the form of thready discharges which pulsate in endless processions. The auric anatomy is our fundamental identity. Physiological anatomy, while dominating the attentions of medical scholars for centuries, is a by-product of the auric anatomy. Physiology is not the seat of our identity. Physiology is an inertial expression, an occlusion in Vril space. Physiology forms "around" auric anatomy, being secondary and subservient to auric dynamics. The auric anatomy is an entity not well studied any longer. Though forming the entire lexicon of ancient medicine, auric anatomy was forgotten with the dissective anatomy of Vesalius. Auric anatomy was dimly perceived in the work of G.S. White, A. Abrams, and T.G. Hieronymus. Auric anatomy became especially well comprehended under the masterful skills of Dr. Ruth Drown. Auric anatomy absorbs eidetic images directly. Eidetic imagery is the nutrient on which auric bodies continue living. The Drown Radiovision System, a true eidetic

viewing instrument, actually enabled shadowgraphic viewing of auric anatomy with no more energetic application than that provided through the ground. Vril powered, these devices could be carefully entuned to peer into the auric anatomy directly. The physiological occlusions of illness could be clearly seen, suspended within the pulsating matrix of the aura.

Auric anatomy is a dendritic structure, laced with the connective threadworks of the external Vril Matrix. One is therefore thoroughly integrated within the surface Vril Strata, drawing existence and consciousness directly from the generative source of consciousness. We each are supplied with fundamental consciousness, one whose depth exceeds our ability or reach. When inertial space enters and dominates a region of ground, life is destroyed in stages. Beginning with conscious diminutions, an infected region of ground gradually manifests bio-decomposition. In severe cases, one observes bio-elimination. In all such cases, Vril does not completely recede. Vril continues to exist in an bio-inaccessible reach. It is then that human artifice must reenter such a region and raise the Vril potentials, so that Vril will rearticulate the conscious integrity of the lost grounds.

Vril is the connective environment and communicative envelope in which we move and have our being. Our own inflections of Vril, when life-affirming, effect a spreading impulse throughout the Matrix from which all can benefit. Negative inflections reside entirely within the confluent inertial space. We are each necessarily interpenetrated by these discharges, the external sustenance of our being. But we are often influenced by thoughts which come from our own bodies with regard to limitations and boundaries. Our bodies are participants in the limited, bounded inertial world. Liberated through such magnified consciousness, one finds that the inertial descriptions, with their limits and bounds, are simply artificial frames set in an endless space of mind. This was why the Templars wanted this knowledge. It was for the same reason that archaic tribes people sought out these energies: for survival and power over the inertial frame.

The Vril Matrix will absorb only patterns of a bioenhancing nature. It is impossible to "transmit" negative states in the Vril Matrix. The antagonistic response is immediate, literally digesting the irritants, their sources, and their designers. The Vril character is one in which all states of vitality are in constant fusion, admixing and permuting into superlative states. The Vril matrix never tolerates the addition or impressment of negativity by deliberate intent. Those who engage in such transmissions become the unfortunate recipients of their own transmissions. The Vril matrix thrusts all negative patterns into the surficial inertial space. This effectively connects directly to those in whom the negative intent found its place of origin. Recognizing these principles, yet unwilling to cease these activities, certain individuals began researching the direct effects of radioelectric transmissions on the environment.

Those who are exposed to the overwhelming Vril biological reply place themselves in grave danger. While most advance the notion that radio station engineers often become ill through

exposure to radiocurrents, there is a fine order of detail which is not much discussed in this regard. Exposure to radiowaves can stimulate healing responses in individuals (Tesla, D'Arsonval, Lahovsky, Rife). How then can the same energies stimulate degenerative processes? Careful examination shows that the interactive antagonism which occurs between radioenergies and Vril response often requires the exile of bioorganisms from the site. Hideously magnified sensate Vril has stimulated the rapid dissolution of inertial space, often permeating bioorganisms beyond the natural ability to withstand. In natural arenas, most bioorganisms rapidly vacate the area in order to escape the magnified black radiance. Magnitudes of these levels accelerate the personal dissolution of absorbed inertia, a process which is painful.

It is imperative that we comprehend our own personally interblended state within the Matrix. Effects of technology on experience spread rapidly throughout the experiential Matrix, bringing either greatly magnified eidetic or inertial states to each recipient. Increased inertial states block extensive free auric projectivity throughout the Vril Matrix. This produces very specific occlusions in both sensation and consciousness, a biotoxic condition through which most auric sensitivity is blocked within a determined experiential range. The utilization of ELF pulsations effectively blocks the population from reaching full consciousness through excessive auric resistance.

Beyond the eidetic occlusive effects, it is entirely possible to entrain recipients into fixed behavioral modes. ELF impulses flow through physiology, coupling with bioneurology. Such regionally applied electrical vibrations cannot be shielded out of experience by ordinary means, entering and infiltrating grounded conductive foundations. ELF vibrations enter physiology and ENTRAIN responses in the autonomic nervous system. Military studies were conducted to determine the exact effects of each vibratory range, originally a Teslian objective. Inertial space occludes the auric anatomy, producing physiology. Physiology shrouds the real solids, the ideal forms upon which material objects are each framed (Platon). These ideal eidetic solids give each material object its peculiar qualities. Terrestrial matter has been contaminated by inertial occlusions. Matter absorbs a certain degree of inertial space, acquiring this contamination. The ideal solids, upon which material objects are each framed, are not "impure". Material objects are all eidetic projections. They are all generated by the external consciousness, by Vril. Therefore, material objects are each, to certain degree, in need of liberation from the inertia which they absorb.

Wilhelm Reich observed the complete neutralization and reversal of radioactive materials under such articulate impressments. His famed accumulators and cloudbusters effectively demonstrated the dangerous interactions occurring between Vril rich currents and radioactive effluxes. It had been found that ground radionic instruments can neutralize electrical energies. This neutralization takes the form of an effect which gradually spreads and grows throughout the grounds into which radionic instrumentation is applied. With no more power than that taken

from the ground itself, pure Vril, one may re-pattern the ground prevalent energies, selectively raising certain patterns and decreasing others. In the process of entuning the ground, one recognizes that electrical systems are directly impacted. Neutralization through radionic application has produced remarkable effects in electrical systems. In certain cases electrical lighting systems were neutralized (Vogel), regional network power systems destroyed (Constable), and local utility power boxes twice deadened (Vassilatos).

Inertial space in fact, has no defense against such permeations of articulate Vril. Despite having potent inertial entrainment potentials, impressments of inertial energy cannot resist Vril dissolution. When appropriately grounded instruments are employed against these onslaughts, it has been experimentally verified that they fail. Surprisingly small instruments have already been used to neutralize the local effects which have been directly linked with the operation of both HAARP and SANGUINE. It is possible to determine when HAARP is on line and active. The ordinary means of determining these are found in the physiological responses. Deep inaccessible neuralgic pain is experienced before the entunement procedure. Once this slight procedure has been completed, the pain and local manifestations of increased inertia confirms the suspicion. A periodic rhythm being established in procedure at sunset and sundown, we are able to demonstrate the decisive removal of the merely inertial effects of both infernal weapons.

Radionic articulations absolutely rule inertial dynamics. It is in the nature of Vril black radiance to have the fundamental dominion over all inertial species, by-products in which radiotechnology now entirely operates. Both designers and engineers attempted to forge their own autonomous technological path, completely ignoring the Vril manifestations which suffused their early devices. In doing this, they effectively separated themselves from the direct Vril empowerment of their systems. The very thought of grounding a blank tuning instrument from ground seems completely laughable. Nevertheless, photographic emulsions and other more objective proof has shown the presence of a neutral black radiant energy having astounding articulate properties. Of the more fundamental and subjective attributes of this energy, one need not bring objective proof. The greater manifestations of Vril articulate threads are found entirely in subjective parameters, and must be experienced. Without the communal experience previously discussed, there is no knowledge of eidetic reality (V.8). The inimicable communal participation, by which Vril energies are distinguished from all other energetic manifestations, prove them to be the world-fundamental infrastructure. Vril precedes all matter, being the generative source from which material realities spring (V.9).

Vril penetrating eidetic currents cavitate inertial space in distinct threads. Dissolving along these threadlines, inertial space relinquishes its hold on consciousness, emotionality, and physiology. Sensitive visionaries realized long ago that inertial space and all of its bio-resistant manifestations can indeed be eradicated. Powerful dissolution in the inertial agglumeration

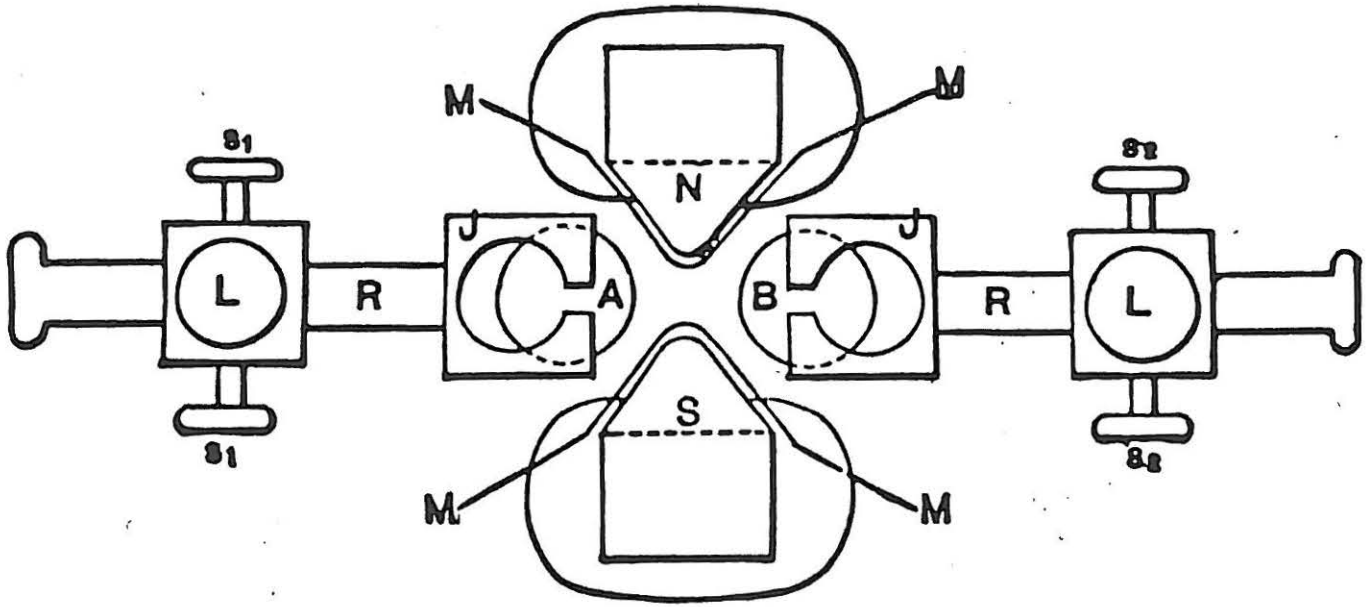
can be secured by the appropriate technological artifice, one of the Vril Technology tenets. In this singular thesis, one recognizes that any IMPRESSMENT of eidetic images can be received anywhere, provided that these fundamental principles are observed.

Inertial forces stimulate the electromagnetic phosphenes (Valentinuzzi). Oculo-neurological effects, the result of peak geomagnetic and geoelectric emissions, have been erroneously cited as the causative agencies in eidetic receptions (Persinger). Phosphenes are typical patterns evidenced when Vril dissolves inertial beams. The Vril Matrix dissolves each densification of inertial space, manifesting the spontaneous appearance of electromagnetic field energy and a host of particulate detritus. Any environmental increase in either is evidence of insensate Vril dynamics. The spontaneous and excessive manifestation of optically visible patterns such as phosphenes marks Vril dynamic events. These ocular patterns do not comprise eidetic images.

Eidetic images are whole, living scenes greatly resembling the nature of remote views. Eidetic imagery forms the constant conscious background, normally ignored and supressed by socially established disciplines. There are societies which do not suppress the constant eidetic flood. Eidetic imagery has been relegated to the realm of "imagination", suggesting that they have no reality apart from the percipient. nevertheless, there are all too-numerous occurences in which free-standing eidetic images have appeared. The famed "Fata Morgana", free-standing living landscapes of extreme detail, have been observed by noteworthy witnesses throughout history. Their observation throughout Victorian times is especially relevant to our discussion (Corliss). These form the legends of parageographic lands and invisible or "hidden" realms. Natural and vagrant radionic entunement of these "phantom topographies" has been cited as the responsible mechanism for their appearance. But these intriguing subjects remain for Compendium Volumes which deal with geopropagation of radiosignals and the WORLD STRUCTURE.

SECTION 2

VLF GENERATORS



NIKOLA TESLA
MAGNETIC ARC
DISCHARGER
1892

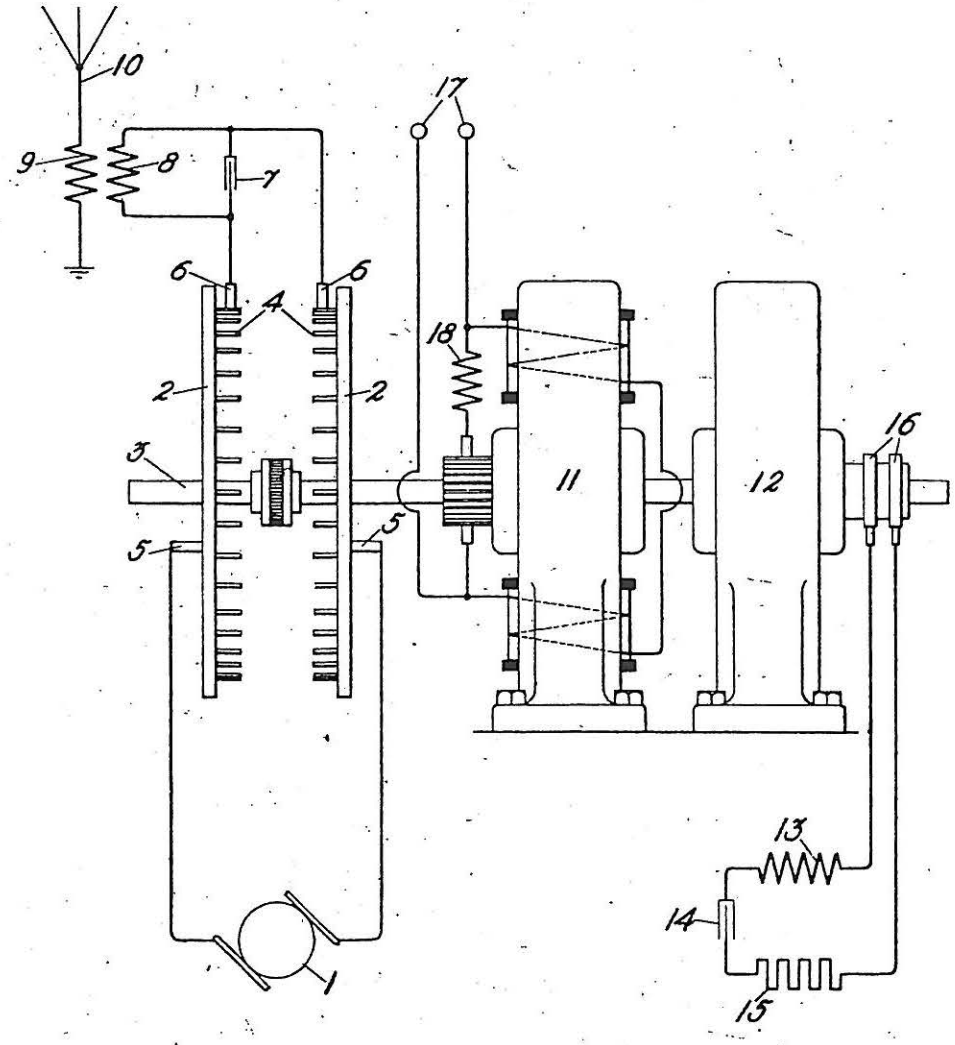
R. A. HEISING.

OSCILLATION GENERATOR.

APPLICATION FILED OCT. 12, 1915.

1,240,206.

Patented Sept. 18, 1917.



Inventor:
Raymond A. Heising.
by A. C. Laurel, Atty.

UNITED STATES PATENT OFFICE.

RAYMOND A. HEISING, OF EAST ORANGE, NEW JERSEY, ASSIGNOR, BY MESNE ASSIGNMENTS, TO WESTERN ELECTRIC COMPANY, INCORPORATED, A CORPORATION OF NEW YORK.

OSCILLATION-GENERATOR.

1,240,206. Specification of Letters Patent. Patented Sept. 18, 1917.

Application filed October 12, 1915. Serial No. 55,396.

To all whom it may concern:

Be it known that I, RAYMOND A. HEISING, a citizen of the United States, residing at East Orange, in the county of Essex and State of New Jersey, have invented certain new and useful Improvements in Oscillation-Generators, of which the following is a full, clear, concise, and exact description.

This invention relates to apparatus for the production of continuous or approximately continuous high frequency oscillations.

Its object is to produce in a circuit high frequency oscillations suitable for wireless telegraphy or the like, by means of apparatus whose operation is not primarily dependent upon the production of a spark to secure sudden increases in voltage. To this end this invention makes use of a mechanical contact-making means, whereby power is supplied to an oscillating circuit by means of a high-voltage direct-current generator at those times during the cycle at which the difference of the voltage between the generator terminals and that across the oscillation circuit is small. The current required to energize the resonant circuit is here supplied conductively by metallic connection to the generator instead of being supplied through a spark gap. In this specification the term metallic connection is used to include those conductors in which metallic conduction takes place, as the ordinary metals, carbon, etc., as distinguished from a connection which transfers electricity by means of a spark or by convection.

This invention will be more fully explained in connection with the drawing which represents a rotating means for periodically connecting the oscillation circuit to the generator, combined with a device adapted to secure constant speed of rotation.

Referring to the drawing, 1 represents a high-voltage direct-current generator, 2 represents two rotatable disks rigidly mounted upon the shaft 3 and insulated from each other. These disks have projecting studs or contacts 4, equally spaced around their circumferences and an equal number on each disk. By means of the brushes 5, the conducting disks 2 are maintained in connection with the terminals of the generator 1 so that the difference of potential between these disks is equal to the electromotive force of the generator. The brushes 6 are arranged to make contact with the studs 4 in such a way that each one of a pair of brushes bears upon a stud at the same instant. The brushes 6 are connected to the two terminals of the oscillation circuit comprising condenser 7 and inductance coil 8, this circuit being tuned to the frequency which it is desired to generate. Another coil 9 is loosely coupled to the coil 8 and serves to transfer power from the above mentioned resonant circuit to a load in which it is to be consumed, for example, to the antenna 10. The shaft 3 is driven by means of a motor 11.

The operation of the system is as follows: At the instant at which the brushes 6 make contact with a pair of studs 4, a rush of current takes place which charges condenser 7 to a voltage equal to that of the generator. Contact is immediately broken with the disks and the condenser discharges through the inductance coil 8. Oscillations are therefore set up in the circuit 7—8, which, if the damping of the circuit, due to the drainage of power from it, and to the resistance in it, is small, are persistent, that is, are very little attenuated as time goes on. After the lapse of a time equal to one cycle, the condenser 7 will again be charged to approximately its original potential difference, this value, however, being slightly less than the original because of the damping of the oscillations. If, at this time, the brushes 6 again make contact with a pair of studs, a sudden rush of current will take place from the generator and renew the charge on the condenser to its original value. Since, however, the loss of charge in the condenser during one cycle is relatively small, the potential difference between the brushes and the disks at the end of the first cycle will also be relatively small, and therefore the transfer of power may take place without the necessity for heavy sparking at the studs when contact is broken. This is in contrast to the ordinary method of operation of such resonant circuits in which a disruptive discharge over a spark gap is relied upon to secure the high voltage necessary to charge the reso-

nant circuit. Since in this device it is essential for proper operation that immediately upon contact of the brush with a stud, a charge shall flow to the condenser, no inductances must be inserted in the generator leads, as is usual in the operation of previous devices depending upon a spark. Since contact is made only at the peak of the voltage wave, the generator will not act as a short-circuit to the resonant circuit, and these inductances may be dispensed with. In order that the operation shall be satisfactory, it is essential that the speed of the motor be such as to insure contact of a brush with a stud once every cycle, or at least once every two or three cycles, so that the decrease in amplitude of the voltage wave, due to damping, shall not be sufficient to produce a spark. Due, however, to the fact that there is then practically no tendency to spark in this device, the studs 4 may be spaced at distances small compared with those distances usual in the devices of the class mentioned in which disruptive discharge takes place. For this reason, although it is required that a large number of studs shall pass each brush per second, still it is not necessary that excessive speeds of rotation shall be employed. The problem of securing sufficiently high mechanical speeds in those devices in which disruptive discharge is relied upon has, as is well known, been a difficult one to solve.

The remainder of the drawing represents a means which may be used with this device for insuring approximate constancy of speed. Here, 12 is an alternating current generator rigidly connected to the shaft 3 or adapted to be positively driven by it. This generator supplies a tuned circuit comprising resistance 15, condenser 14 and inductance 13, connection being made to it by means of the slip rings 16. This resonant circuit may obviously be included in the armature of the alternator itself, but is here shown outside for the sake of clearness. It will be obvious that when the alternator is driven at a speed corresponding to the resonant frequency of the tuned circuit, the power dissipated in the resistance of that tuned circuit will be a maximum, since the current in it will be a maximum. This fact is made use of in securing speed regulation in the manner to be described later. The motor 11 is supplied from a source of constant voltage 17, and has included in its armature circuit a resistance 18. Recalling that the effect of such a resistance upon the operation of the direct current motor is to lower the effective voltage over the terminals of the latter as the load increases, the method of maintaining constant speed will now be apparent. Suppose that the resonant circuit 13, 14, 15 is tuned to a frequency slightly higher than that which would be developed were the alternator running at the speed required for operating the contact-making device. Then, if for any reason the speed of the alternator increases, a larger current will be set up in the tuned circuit, which will consequently increase the load upon the alternator 12, and therefore also on the motor 11. But the effect of this increase in load is, as stated before, to lower the effective voltage over its terminals, and the speed of the shaft will therefore tend to fall again to its original value. On the other hand, if the speed of the motor is decreased, the frequency developed by the alternator will depart still more from that required for resonance, the load on the generator and motor will decrease, the voltage over its terminals will increase, and consequently the speed will tend to rise again to the correct value.

What is claimed is:

1. In an oscillation generator, the combination of a source of electromotive force, a complete oscillation circuit, means for periodically connecting said circuit to said source and for periodically isolating said circuit from said source.

2. An oscillation generator comprising an oscillation circuit having a constant natural frequency, a source of electromotive force, means for supplying said circuit from said source at times differing by integral multiples of a natural period of said circuit, and translating means associated with said circuit.

3. An oscillation generator comprising an oscillation circuit having a constant natural frequency, a source of electromotive force, contact-making means for establishing a metallic connection between the terminals of the resonant circuit and the terminals of the source of electromotive force at times differing by integral multiples of a natural period of said oscillation circuit, and translating means associated with said circuit.

4. An oscillation generator comprising an oscillation circuit having a constant natural frequency, a source of electromotive force, contact-making means for establishing a metallic connection between the terminals of said circuit and of said source at those times at which the potential difference between the terminals of the oscillation circuit and those of the source of electromotive force is relatively small, and translating means associated with said circuit.

5. An oscillation generator comprising a resonant circuit having a constant natural frequency, a source of electromotive force and a rotating contact-making means whereby current is supplied by metallic conduction from said source to said circuit at those times at which the voltage over said contacts is relatively small.

6. An oscillation generator comprising a resonant circuit, a source of electromotive force, a rotatable member carrying two sets of equally spaced contact studs, one of each of said sets being connected respectively to a terminal of said source, two brushes connected with said resonant circuit, said brushes being adapted to make metallic connection respectively with a stud of each set, and means for rotating said member.

In witness whereof, I hereunto subscribe my name this 7th day of October A. D. 1915.

RAYMOND A. HEISING.

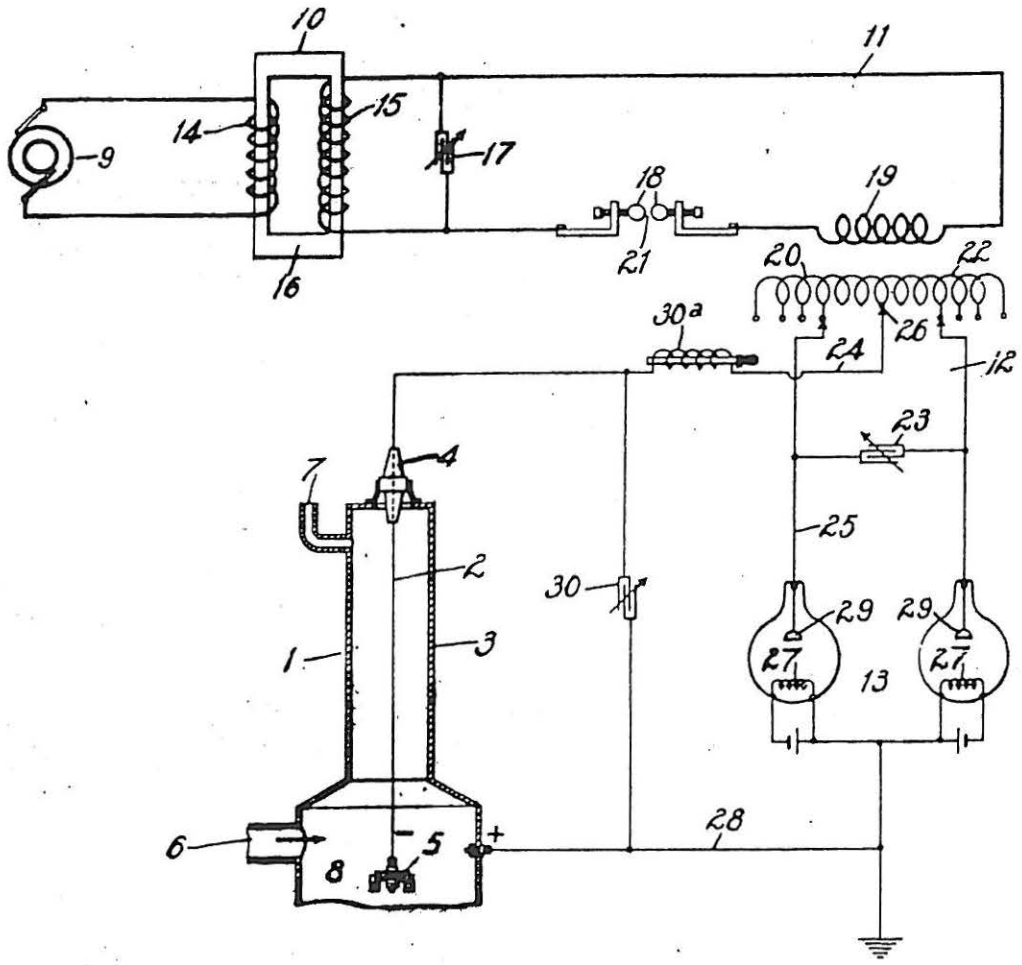
Copies of this patent may be obtained for five cents each, by addressing the "Commissioner of Patents, Washington, D. C."

L. W. CHUBB.

ELECTRICAL TRANSFORMING AND RECTIFYING SYSTEM.

APPLICATION FILED FEB. 10, 1916.

1,257,978. Patented Mar. 5, 1918.



WITNESSES:

R. J. Fitzgerald.

Geo. A. Hansen.

INVENTOR

Lewis W. Chubb.

BY

Wesley G. Carr

ATTORNEY

UNITED STATES PATENT OFFICE.

LEWIS W. CHUBB, OF EDGEWOOD PARK, PENNSYLVANIA, ASSIGNOR TO WESTINGHOUSE ELECTRIC AND MANUFACTURING COMPANY, A CORPORATION OF PENNSYLVANIA.

ELECTRICAL TRANSFORMING AND RECTIFYING SYSTEM.

1,257,978. Specification of Letters Patent. Patented Mar. 5, 1918.

Application filed February 10, 1916. Serial No. 77,416.

To all whom it may concern:

Be it known that I, LEWIS W. CHUBB, a citizen of the United States, and a resident of Edgewood Park, in the county of Allegheny and State of Pennsylvania, have invented a new and useful Improvement in Electrical Transforming and Rectifying Systems, of which the following is a specification.

My invention relates to systems of electrical distribution and especially to means for transforming an alternating current of a relatively low potential and frequency into a high potential rectified or unidirectional current that may be employed for producing electrical discharges in one direction only.

More particularly, my invention refers to transforming means of the above-indicated character which may be employed in electrical systems operating at high voltages, such as obtain in the systems employed for precipitating finely divided particles of matter originally held in suspension in bodies of gas or vapor by the application of electric charges. Moreover, my transforming system may be utilized for exciting Röntgen-ray and similar tubes, and also for other service which may require the utilization of high-potential electrical discharges.

For the service conditions indicated, and, more especially, for separating suspended particles from gaseous bodies, it is desirable to operate at such voltages as will insure the formation of electrical discharges. To illustrate, the most effective method for precipitating electrically necessitates the production of silent electrical non-disruptive discharges or corona emanations. In accordance with the principles disclosed in United States Patent No. 1,067,974 to F. G. Cottrell, this method contemplates maintaining a non-disruptive discharge at maximum potential through the gaseous body to be precipitated, the negative potential being applied, preferably, at the surface from which the corona discharges emanate and being of such a value as to be in excess of that which may be maintained when the positive potential is applied to the said surface. Consequently, the discharge surface is maintained at a very high negative electrical potential in order to produce corona or silent electrical discharges in one direction only.

Inasmuch as it is difficult to accomplish the aforementioned result by applying a direct-current voltage of the requisite potential, the desired result has heretofore been obtained by employing an alternating-current, high-potential transformer in combination with a rectifier which, in practice, has been, almost without exception, a mechanical rectifier. The difficulties involved in subjecting mechanical rectifiers to service conditions involving such high-voltages are numerous and well known, and, as a substitute therefor, I propose to employ an asymmetric conductor or hot-cathode electron rectifier in combination with the attendant circuits to be disclosed in the following description.

In the system of the present invention, a source of power supply of relatively low frequency and low potential is employed in connection with a high-frequency discharge circuit which is magnetically interlinked with an auxiliary circuit embodying a hot-cathode rectifier or asymmetric conductor, the latter being utilized to rectify the high-potential, high-frequency alternating currents thus produced to effect corona discharges in one direction only from one of the electrodes of an electrical precipitating device. Again, the high-frequency circuit is resonated with the auxiliary circuit magnetically interlinked therewith, thereby producing a very efficient transformation or interchange of electrical energy. For the accomplishment of these ends, and for other objects which will be hereinafter pointed out, I have invented a transforming and rectifying system, the characteristics of which will be fully pointed out in the following description and the accompanying drawing, in which the single figure is a diagrammatic view of an electrical precipitating system embodying a form of my invention.

In the figure, a smoke precipitator 1 is furnished with high-potential unidirectional current through the circuits 11 and 12, the former of which is supplied with high-potential alternating current through a transformer 10 and an alternator 9.

As mentioned above, the smoke-precipitating device shown at 1 utilizes high-potential voltages which will effect electrical discharges in one direction only. It is well known that negative-corona emanations are more effective in precipitating suspended

particles than positive-corona emanations. In accordance therewith a central conductor 2 of the smoke precipitator is projected into the flue or stack 3 and insulated therefrom by means of an insulating bushing 4 and an insulating support 5. The centrally-disposed discharge electrode 2 is so connected in circuit that it is subject to negative potential at all times, and the smoke-stack 3 likewise is continually charged to a positive potential. The stack 3 is provided with an inlet 6 through which the gaseous body to be precipitated is admitted and with an outlet 7 through which the gaseous body, after having its suspended particles removed therefrom, is emitted. As mentioned above, the electrode 2 emits negative corona discharges which, in turn, impart electrical charges to the particles held in suspension in the gaseous body to be precipitated. The precipitated particles will deposit upon the walls of the smoke-stack 3 and will be collected in a chamber 8 provided at the bottom of the precipitator.

In order to produce negative-corona emanations from the discharge electrode 2, a source of power supply shown as a single-phase alternator 9, is connected through a transformer 10, a high-frequency circuit 11, and an auxiliary circuit 12, to a rectifier 13. The rectifier 13 is so connected to the smoke precipitator that negative potentials only will be impressed upon the discharge electrode 2.

The alternator 9 is connected to a primary winding 14 of the transformer 10, the secondary winding 15 thereof being magnetically interlinked with the primary winding 14 by means of the magnetizable core member 16. The secondary winding 15 is connected in shunt to an adjustable condensive reactance element 17 and the high-frequency discharge circuit 11, the latter comprising adjustable spark-gap members 18 and a primary winding 19 of an air-core transformer 20. The secondary transformer winding 15 is so designed that a sufficiently high potential may be impressed upon the condenser 17 to effect a spark discharge across the air gap 21 of the spark gap members 18. By properly adjusting the electrical constants of the transformer primary winding 19 and the condensive reactance 17, very high-frequency oscillations may be produced in the high frequency circuit 11 when the spark gap 21 is disrupted, the condenser 17 and the inductive primary winding 19 being connected in series relationship to form a tuned or series resonant circuit. A secondary winding 22 of the air-core transformer 20 is placed in inductive relation with the primary winding 19. Another condensive reactance element 23 is connected in shunt to the secondary winding 22 and its electrical constants are so adjusted that the auxiliary circuit 12 will be in electrical resonance with the high-frequency discharge circuit 11 when oscillations are set up therein by reason of the spark discharges disrupting the air gap 21. In this manner, a very high-frequency and high-potential oscillation is produced in the auxiliary circuit 12 which is interconnected through a conductor 24 and adjustable leads 25 to the rectifier 13. The conductor 24 is connected to a mid-point tap 26 on the secondary transformer winding 22 and also to the discharge electrode 2. The cathode 27 of the rectifier 13 is connected, by means of a conductor 28, to the smoke stack 3. It will be apparent, therefore, that a complete circuit for the rectified current is established through the conducting space intermediate the discharge electrode 2 and the inclosing flue or smoke stack 3 of the smoke precipitator. It will be noted that the rectifier 13 is connected to the secondary 22 of the transformer 20 in the usual way, the two anodes 29 thereof being alternately charged as the high-frequency oscillation in the circuit 12 reverses its sign. The potential, therefore, existing between the electrodes 2 and 3 of the smoke precipitator 1 will be equal to one-half of the peak value of the voltage induced in the secondary winding 22, since the discharge electrode 2 is connected to the aforesaid mid-point tap on the transformer-secondary winding. In order to make the negative-corona emanations issuing from the discharge electrode 2 more steady, a condensive reactance element 30 is connected in shunt to the conductors 24 and 28 which is utilized to store the energy and regulate its subsequent discharge between the electrodes 2 and 3, and a reactance coil 30^a is inserted, as shown, to sustain the rectified current, as is well known in the art. The action of the condenser 30 may be considered as being similar to that of a fly-wheel associated with a motor-generator set whereby the peak loads are furnished with energy through the inertia of the fly-wheel and the device 30^a serves to maintain a constant flow of energy into the condenser.

It is known that the smoke precipitator 1 is subject to break downs when the conditions of the gaseous body flowing therethrough are considerably varied from normal. It is, consequently, important to protect the apparatus in circuit from the stresses or strains that may result from such a break-down. When a break-down occurs, the potential difference between the electrodes 2 and 3 will be substantially reduced, and the resonance of the auxiliary circuit 12 will be consequently disturbed because of the change in the electrical conditions obtaining in the circuits associated with, and supplied with power from, this auxiliary circuit. The tying-together of, or the resonance conditions existing between, the cir-

cuits 11 and 12 will be consequently disrupted, and small quantities of energy only will be transferred to the auxiliary circuit 12 because of said auxiliary circuit being forced out of step or out of resonance with the discharge circuit 11. The apparatus, therefore, will be protected against short circuits, such as may occur in the smoke precipitator 1, since the energy supplied to the rectifier 13 will be limited in amount and insufficient to maintain the break down conditions previously established in the precipitator.

From the foregoing description, it will be noted that no low-frequency, high-potential transformer is employed, such transformers being very expensive to construct and unreliable in operation because of the insulating difficulties involved. The transformer 20 which essentially is an equivalent of a Tesla-coil, being of an air-core type, is a relatively cheaper one to construct, and, by associating the transformer 20 with the high-frequency oscillation circuit 11, superior results may be obtained in effecting high-potential discharges. By associating the rectifier 13 with the secondary winding 22 and the high-frequency and high-potential auxiliary circuit 12, rectified currents of very high potentials may be obtained for operating the smoke precipitator 1.

While I have shown two hot-cathode electron rectifiers as comprising the rectifier or the asymmetric conductor for rectifying the alternating current, it will be understood that other asymmetric conductors may be suitably employed without departing from the spirit and scope of the appended claim.

I claim as my invention:

In a distributing system, the combination with a relatively low-potential and low-frequency alternating-current circuit, a high-frequency oscillating circuit, and means to effect a transformation of energy therebetween, of a second high-frequency high-potential circuit that comprises an asymmetric conductor magnetically interlinked with said first high-frequency oscillating circuit and tuned to resonate under normal conditions therewith, and a distributing circuit for the rectified currents delivered through said asymmetric conductor, said distributing circuit having a translating device that is subject to breakdowns when the resonant conditions normally obtaining between said high-frequency circuits are disturbed, whereby the energy supplied to said translating device may be limited to a safe value.

In testimony whereof, I have hereunto subscribed my name this 31st day of Jan. 1916.

LEWIS W. CHUBB.

Copies of this patent may be obtained for five cents each, by addressing the "Commissioner of Patents, Washington, D. C."

Dec. 11, 1923. 1,477,271

F. LOWENSTEIN

MULTIFREQUENCY GENERATOR

Original Filed Dec. 9, 1918

Fig. 1.

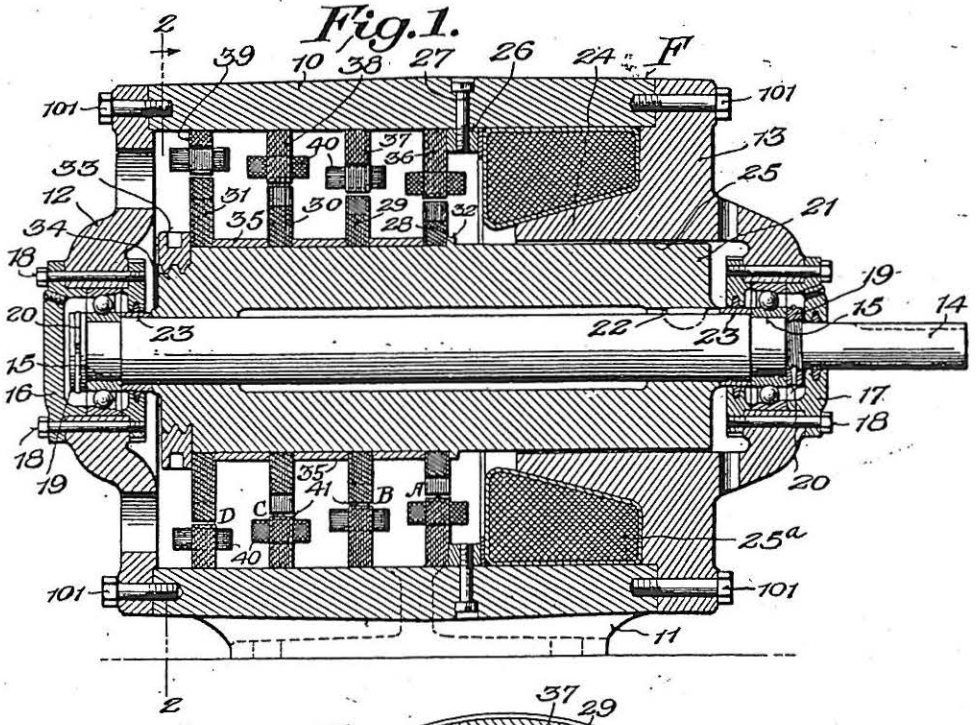
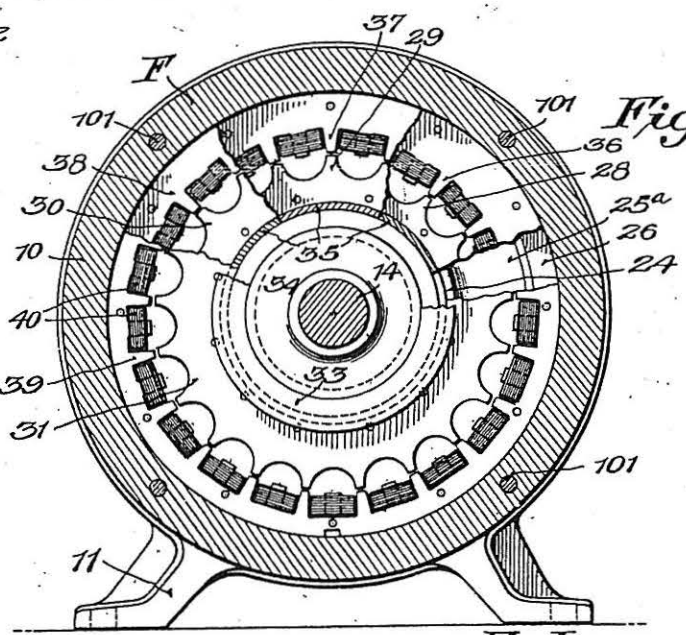


Fig. 2.



Witness

Chas. L. Griesbauer

Inventor

F. Lowenstein,

By M. C. Massie

His Attorney

Patented Dec. 11, 1923. 1,477,271

UNITED STATES PATENT OFFICE.

FRITZ LOWENSTEIN, OF BROOKLYN, NEW YORK; JOHN C. WAIT ADMINISTRATOR OF SAID FRITZ LOWENSTEIN, DECEASED, ASSIGNOR TO WILLIAM DUBILIER, OF NEW YORK, N. Y.

MULTIFREQUENCY GENERATOR.

Application filed December 9, 1918, Serial No. 265,930. Renewed September 13, 1923.

To all whom it may concern:

Be it known that I, FRITZ LOWENSTEIN, a citizen of the United States, residing at Brooklyn, in the county of Kings and State of New York, have invented certain new and useful Improvements in Multifrequency Generators; and I do hereby declare the following to be a full, clear, and exact description of the invention, such as will enable others skilled in the art to which it appertains to make and use the same.

This invention relates to dynamo electric machines and particularly to a multi-frequency generator especially suitable for use in connection with wireless telegraph apparatus.

One object of my invention is to produce a simple and compact generator from which currents at any one of several different frequencies may be obtained selectively at any given speed.

The field winding that produces the magnetizing flux in generators may, at times, be damaged by burn-out or otherwise; and it is therefore another object of this invention to provide a generator construction in which the field winding is supported in or on the enclosing generator frame or housing in such manner that it shall be readily removable and replaceable independently of the other main elements of the machine and without disturbing such elements, whereby repair or replacement of the winding is greatly facilitated.

Still another object of the invention is to provide a construction in which the rotors and their supporting means are of such form and arrangement as to be easily insertable into and removable from the generator housing without disturbing the other parts of the generator.

In an especially desirable construction in which the objects of my invention are attained, I provide a structure embodying a plurality of spaced stators, respectively coaxial with rotors carried by a shaft mounted within the frame or housing of the dynamo electric machine, the removable end wall of which has a boss that projects axially into the frame and partly houses the field winding which is mounted in coaxial relation to the sets of rotors and stators, and most advantageously adjacent said end wall. This manner of mounting the field winding permits the removal of the winding axially from the housing without disturbing the sets of rotors and stators. The sets of rotors and their support, considered as a whole, form what may be described as a generally conical structure fitting within the complementarily disposed sets of stator. The rotor structure is therefore axially movable into and out of the housing with a maximum of ease and convenience. The construction thus generally described and more fully hereinafter explained is a particularly advantageous one; but to attain the same objects, other constructions may be provided that, nevertheless, embody the principles of my invention. It is to be understood that the principles of the invention can be embodied in both motors and generators.

The objects and novel features of my invention will be apparent from the following description taken in connection with the drawing, illustrating a typical construction within the invention.

Fig. 1 is a longitudinal central sectional view of a multi-frequency generator embodying my invention, and

Fig. 2 is a transverse sectional view of the same, taken on the line 2—2 of Fig 1, showing parts broken out to more clearly disclose the construction of the stators, rotors, and magnetizing field winding.

Referring to the drawings, the generator frame or housing F comprises a hollow substantially cylindrical body 10, provided with feet 11, and end shields or walls 12 and 13, secured to the ends of the body 10 by bolts 101. These walls close the ends of the body and are readily removable therefrom. The generator is provided with a driving shaft 14 mounted in ball bearings 15, 15, carried in central openings in the end shields 12 and 13. The bearings 15, 15 are held in position by suitable bearing retainers 16 and 17, secured to the end shields by the bolts 18, the bearing retainer 17 secured to the end shield 13 having a central opening therein through which one end of the shaft 14 projects, and is arranged to be coupled to a device, such as an electric motor, for driving the generator. The inner races of the ball bearings 15, 15 are retained in position, abutting shoulders provided on shaft 14, by nuts 19, locked to the shaft 14 by springs 20.

The shaft 14 carries a rotor-supporting sleeve or hollow cylinder 21 keyed thereto

at 22 and limited against endwise movement thereon by the rings 23 disposed within the bearing retainers 17 and abutting against the inner edges of the inside races of the ball bearings 15. The end shield 13 has an integral inwardly projecting boss 24 provided with a bore 25 that is of sufficient diameter to receive the sleeve 21 the air gap between the sleeve and shield being as small as possible. The outer surface of the boss 24 tapers inwardly to partly encase the annular field winding 25^a which produces the magnetizing flux for all the rotor-stator sets. The winding 25^a is held in place against endwise movement in said housing by the end plate or shield 13 and the retaining ring 26 that is secured to the body 10 by bolts 27.

The rotor-supporting sleeve 21 is adapted to support a number of rotor structures, depending on the number of frequencies desired. In the present instance, the generator is designed to generate at any one of four different frequencies and accordingly I have shown four rotor structures, 28, 29, 30, and 31, supported thereon, the rotor structures being built up of laminations and constituting the rotating elements of the rotor-stator sets A, B, C and D. The end rotor 28 abuts against the shoulder 32 on the sleeve 21 and the other end rotor 31 is held in place by a nut 33 that is secured on the screw-threaded reduced end 34 of the rotor sleeve. The intermediate rotors 29 and 30 are spaced from the end rotors 28 and 31 and from each other by spacing rings 35.

The number of poles on the rotors 28, 29, 30 and 31, differ from each other so that when the shaft 14 is rotated at any given speed, currents of a plurality of different frequencies will be generated. In the present instance, the number of poles on the rotors 28, 29, 30 and 31, are 18, 19, 20 and 21, respectively, the range being small so that the frequencies produced at one speed, say 2700 r. p. m., are 810, 855, 900 and 945 cycles per second, for example, and, therefore, do not differ very greatly from one another, but afford a number of currents of differing frequencies, selectable as desired. The several different frequencies are simultaneously produced and, therefore, current at different frequencies may, if desired, be supplied simultaneously from the generator. It is to be understood that it is not necessary that the stated speed of rotation and pole number be adhered to, inasmuch as these may be altered to suit various conditions and permit the generation of currents of different frequencies, as desired. The rotors are progressively of greater external diameter from the rotor 28 to the rotor 31 that is farthest removed from the winding 25. By this arrangement the teeth or poles on the rotors may be kept of the same circumferential length, so that the same size dies may be used in cutting the teeth or poles of the various laminations from which the rotors are built. In the present instance, four stators, 36, 37, 38, and 39, are secured to the inner side of the frame 10, the stators being positioned opposite the rotors 28, 29, 30 and 31, respectively, and each stator being provided with the usual windings 40. This coned or stepped arrangement of the cooperating rotor and stator sets renders it a very simple matter to slide the stators and their support out of the housing without in any way disturbing the other parts of the machine, the end place 12 b ng first removed, of course, to permit this operation.

Suitable terminals (not shown) are provided, to which the windings 40 of the stators are connected, and from which current may be supplied at the different frequencies to a load circuit or circuits. Current for the exciting field winding may be supplied by some suitable source, such as a direct current generator. All of the metallic parts of the magnetic circuit, that is, the sleeve 21, the laminations of the rotor-stator sets A, B, C and D, the frame 10 and the end shield 13, should be of high permeability in order to provide a path of low reluctance for the magnetic flux.

The operation of the generator will be understood from the foregoing description. The shaft 14 being driven at a suitable speed and the exciting coil 25^a being energized, current may be generated at four different frequencies in the generator illustrated, and for any change of speed the frequencies of the four sets of rotor-stator elements will change accordingly. A damaged field winding may readily be removed by taking off the end shield 13, and sliding the winding out of that end of the housing, without disturbing the rotor-stator elements and other parts of the machine, and similarly, the rotor sets and their support can be readily moved out of the other end after removing shield 12, as already explained. These features are particularly desirable in machines used for wireless communication, where practically uninterrupted service is essential. The generator illustrated as an example, is of ½ kilowatt capacity, being designed for use with wireless telegraph transmitting devices and developing 10 amperes at 50 volts, when driven at 2700 revolutions per minute. However, the size and the application of the generator are not limited to those given.

While I have shown and described the dynamo electric machine in detail, it will be understood that various features thereof may be modified without departing from the spirit and principles of my invention.

I claim:

1. In a dynamo-electric machine, the com-

bination with a plurality of stators arranged in sets of different internal diameters, of a corresponding number of rotors arranged in sets of different external diameters respectively cooperating with the sets of stators, said diameters decreasing regularly from one end of the machine toward the other, and means for producing a magnetizing flux in said stators and rotors.

2. In a dynamo-electric machine, the combination with a frame, of a plurality of sets of stators secured therein, said sets of stators being of different internal diameters and having poles of substantially the same size, said diameters decreasing regularly from one end of the machine toward the other, windings on said stators, a rotatable shaft mounted in said frame, a plurality of sets of rotors removably mounted as a structural unit on said shaft and respectively disposed concentrically to said sets of stators, said sets of rotors being also of different external diameters corresponding to the stator set diameters and having poles of substantially the same size, a separable housing plate at the end of the frame adjacent the stator set of greatest diameter, and means whereby a magnetizing flux is produced in said rotors and stators.

3. In a dynamo-electric machine, the combination with housing means provided with removable end walls, of a plurality of sets of cooperating rotors and stators removably disposed within said frame, said sets decreasing in diameter from a location adjacent one of said end walls, and a field winding removably disposed adjacent the other end wall.

In testimony whereof I hereunto affix my signature.

FRITZ LOWENSTEIN.

Witness:
P. A. NEWMAN.

May 1, 1934. A. BRASCH ET AL 1,957,008

IMPULSE GENERATOR

Filed Sept. 11, 1931

Fig. 1.

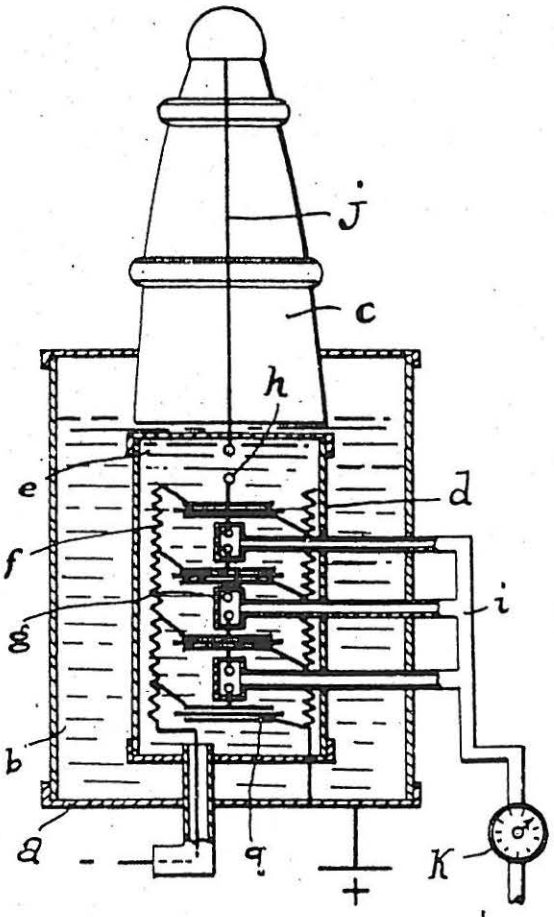


Fig. 2.

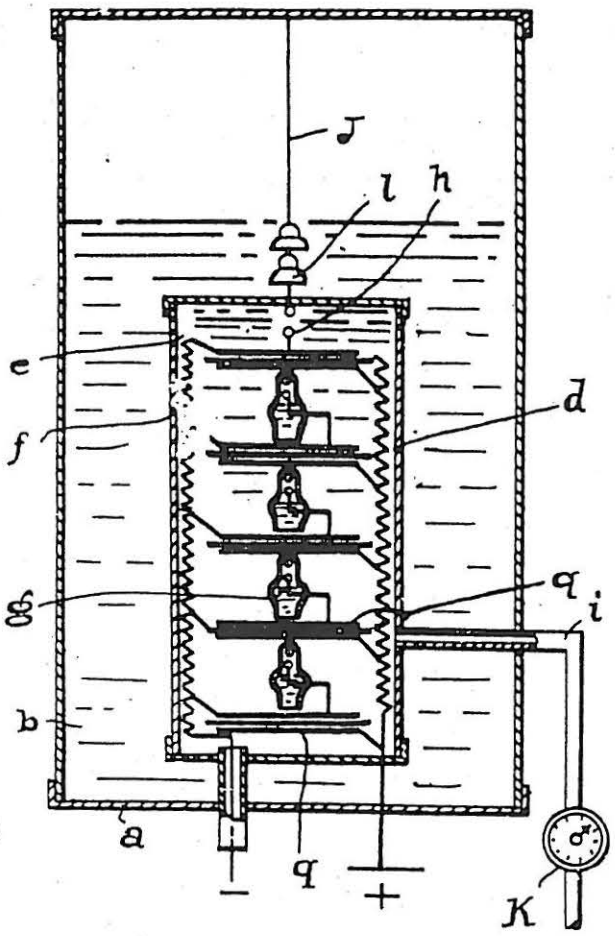
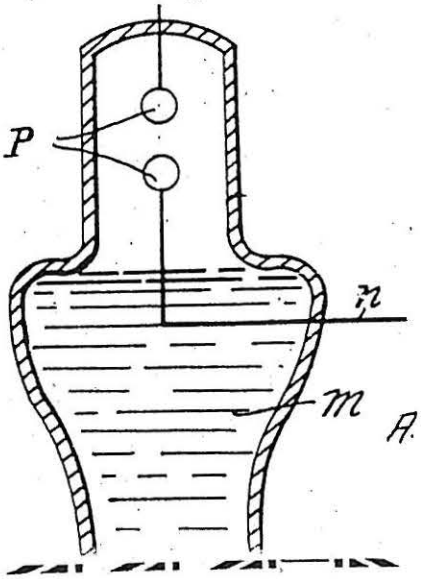


Fig. 3.



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ATTORNEYS.

Patented May 1, 1934 1,957,008

UNITED STATES PATENT OFFICE

1,957,008

IMPULSE GENERATOR

Arno Brasch, Fritz Lange, and Max Dahl,
Berlin, Germany

Application September 11, 1931, Serial No. 562,406
In Germany September 11, 1930

14 Claims. (Cl. 171—97)

As a very recent innovation in the art, an ever-increasing tendency is making itself noticeable to acquire the assistance of extremely high voltages, if only by way of impulse or intermission, for testing purposes in the trade, or for the purpose of scientific investigation. In this connection reference may be made to the testing of open line insulators and the generation of traveling waves, wherein the principal feature concerned is the generation of voltages of approximately that strength in which the same might occur assuming the line were struck by lightning, i. e., a strength amounting to several million volts.

It is also a fact that quite recently various problems of an acute nature have cropped up, which are conditional on the generation and control of high electrical potentials. Thus, for example, with the assistance of these potentials, efforts have been made with the help of corpuscular rays accelerated in high vacuum tubes to exert influence on the inner atomic structure of matter, and to produce conversion of elements. Particularly in experiments of this nature, in which merely the average output constitutes the important factor, the impulse or intermission process is equivalent if not superior to continuous operation such as derived by the use of Tesla or alternating current, as for short-time operations it is possible to employ in the construction of these apparatus materials having a much lower power of insulation, since for brief spaces of time the resistance of more or less inferior insulating materials is still extremely high.

Beyond this it is also possible to employ extremely high impulse voltages for medicinal purposes in such cases in which the desired object is the treatment in intensive form with rays resembling those of radium, i. e., channel and cathode rays, whereby, owing to the considerable intensities concerned, the period of radiation naturally is required to be very short, a bundle of channel rays of 1 milliampere and potential of several million volts being equivalent to the intensity of radiation of approximately 100 kilogrammes of radium.

The impulse apparatus used heretofore and generally speaking constructed according to the method of E. Marx, are operated exclusively in air by atmospheric pressure. The Marx device consists of an arrangement whereby a plurality of condensers are charged in parallel through resistors of such a value that when the charge reaches a predetermined value the condensers are automatically discharged in series with a load circuit, thereby securing a discharge voltage which is for a very small interval of time much larger than the charging voltage. If, however, it is a question of several million volts, these apparatus, owing to the large amount of space required, will be capable of production only at very large expense, so that the same are hardly available to small institutions or undertakings, and more particularly laboratories or medical institutions.

It is, therefore, the primary object of the present invention to provide a reliable and compendious type of apparatus for any desired voltage such as required for testing or atomic purposes. Other objects and advantages of the invention will become apparent as the description proceeds.

It is well known that insulating liquids possess for a brief space of time a very considerable disruptive strength. Whereas, generally speaking, a disruptive strength of field amounting to 40,000 to 60,000 volts/cm. is assumed in respect of commercial oil, and one of 200,000 to 300,000 volts/cm. in respect of very pure oils, this value when subjected to impulse action increases dependent on the duration of the impulse (10^{-3}–10^{-8} sec.) to 500,000–1,300,000 volts per cm.

Numerous experiments conducted have shown that the disruptive value is approximately the same with all kinds of oil, including very impure oil, and that it is merely the duration of the impulse which constitutes the decisive factor, so that operations may accordingly be performed with cheap and impure oil. Since the final high voltage is only effective for an extremely brief space of time, it is obviously the correct thing to embed impulse voltage systems of this kind in liquid insulating materials. However, the fact of the delay above referred to in the case of brief periods of time also discloses that it is impossible to also allow the operation of the spark gap to be initiated simultaneously under oil, as in this case an increase of voltage up to ten times the amount would be required. According, therefore to the invention, the spark gaps are located in separate chambers containing gas under pressure, whereby, according to the tests made, a delay which is capable of measurement does not take place. This combination has the advantage that the large ball gaps otherwise necessary in the case of normal impulse apparatus are entirely obviated, and the whole connection may be performed in small, handy chambers. It is well known that the disruptive strength of gases increases up to about 70 atmospheres in proportion with the prevailing pressure. If, therefore, the spark distance in atmospheric pressure amounts at a certain voltage between points to 10 cm.,

this distance at a pressure of 10 atmospheres will amount to only 1 cm. However, it is naturally quite possible to provide for any desired pressure in the small chambers. An additional advantage resides in the fact that the regulation of this gap in order to produce different voltages is not, as heretofore, performed mechanically, but may be effected simply by increased or decreased compression in the chambers, and the pressure measured on a manometer.

In order to avoid creeping discharges at the condensers the insulating liquid employed may be placed under a certain pressure to preclude any possibilities in this direction. In this manner the disruptive strength of the solid dielectric is at the same time greatly increased. The tendency to sliding discharge, which is produced by high frequency occurrences upon the connection, may also be very greatly diminished by the use of an insulating liquid having a high dielectric constant.

To avoid large dimensions of the pressure container, or to confine the use of high-quality insulating substances to a minimum, this container is made only of a sufficient size to just receive the condensers, and is placed in a second larger container. Since the liquid in this second container is acted upon only by the final impulse voltage, and not by the charging voltage acting for some length of time, it is possible to employ in this outer container relatively good conductive liquids, for example water. When using relatively good conductive liquids it is then naturally necessary to provide an additional spark gap, so that the charging voltage is at no time in connection with the poor external resistance of the liquid, but that on the other hand the high voltage impulses are connected with the liquid, via the gap, so that undesirable ruptures do not occur at other points. The very possibility of being able to employ a cheap substance, such as water, as insulating liquid should permit of voltages of 50,000,000–100,000,000 volts. In order to avoid appreciable ruptures, impulse generators of the kind described permit the placing of the articles to be tested, such as insulators or discharge tubes, in the outer container, and to be operated with high voltage.

The invention will now be described more fully with reference to the accompanying drawing, in which

Fig. 1 shows diagrammatically a longitudinal section through an impulse generator.

Fig. 2 is a similar view of a modified form of embodiment.

Fig. 3 is a longitudinal section on enlarged scale taken through the communicating pressure spark gap employed in the impulse generator according to Fig. 2.

Referring now to the drawing, *a* is an outer container preferably composed of metal and wholly or partially filled with insulating oil *b* of poor quality. In place of the oil it is also possible to employ water. In Fig. 1c is the insulated passage conducting the impulse to the desired apparatus, for example X-ray tube or other medicinal apparatus. There may also be connected with the passage insulators or other apparatus for the purpose of testing the disruptive strength. Within the outer container *a* there is provided an inner container *d*, which is filled with oil *e* of a higher quality, or having a greater specific inductive capacity respectively. In this vessel *d* there are furnished charging resistances *f*. The one resistance is joined up with the charging voltage, while the second resistance is connected with earth. In the container *d* there are aiso situated the spark gaps *g*, which by means of insulated pipes *i*, which include a manometer *k*, are connected with a compressed air source. A special series spark gap *h* is provided at the end of the gap *g*. The one ball of the gap *h* is in accordance with Fig. 1 connected by the line *j* with the reception pole of the impulse generator, whereby this line *j* at the point where the same is passed through the insulator *c* is insulated against the outer container. Between the single gaps there are situated the capacities or condensers *q*, the armatures of which are connected on the one hand with the charging resistance, and on the other hand with the particular poles.

By regulating the compressed air conducted to the single spark gaps through the pipes *i*, in which connection the pressure may be read on the manometer *k*, it is possible to graduate the manometer to constitute a voltmeter, and to employ the same in this capacity. The voltage may, therefore, be varied as desired within different limits, in accordance with the degree of pressure, which may be adjusted by means of valves or the like.

The form of embodiment according to Fig. 2 agrees in substance with that in Fig. 1. In this case, however, there is introduced into the container *a* the apparatus *l* which is to be tested as regards its disruptive strength.

In Fig. 2, therefore, there is shown an insulator applied directly to the series spark gap *h* and tested in the apparatus itself. In place of the insulator *l* there may be fitted a discharge tube, so that the rays emanating from the discharge tube pass directly from the interior of the apparatus towards the outside on to the article or object under treatment.

In the embodiment according to Fig. 2 the spark gaps are located in chambers, which are open towards the oil space of the outer container *d*, so that the oil is capable of penetrating in part into the same. The oil space itself is connected by means of a pipe *i*, over a manometer *k*, either with a compressed air source or with an oil feed pipe, which may be maintained under pressure as desired. In contradistinction to the form of embodiment in Fig. 1 the single air pipes communicating with the spark gap chambers are omitted in Fig. 2. In the latter embodiment the pressure is conveyed evenly by the oil or other liquid, so that all spark gaps are under the same pressure.

Fig. 3 shows on enlarged scale one of the spark gaps employed in Fig. 2. In this figure *m* is the oil rising in the chamber under the pressure of the oil, while *n* is the lead to a spark gap pole *p* and *o* the lead to the second pole *p*.

It will be understood that no restriction is made to the specific forms of embodiment shown in the drawing, and that various modifications are quite possible within the meaning of the above description and the annexed claims without departing from the spirit of the invention.

What we claim as new and desire to secure by Letters Patent is:

1. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid within the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers

through the medium of the said resistances, gas-filled chambers, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

2. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid of high specific inductive capacity within the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, gas-filled chambers, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

3. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid within the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a pressure exceeding atmospheric pressure, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

4. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid of high specific inductive capacity within the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a pressure exceeding atmospheric pressure, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

5. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid within the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a regulable pressure exceeding atmospheric pressure, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

6. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid of high specific inductive capacity within the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a regulable pressure exceeding atmospheric pressure, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

7. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid under pressure in the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, gas-filled chambers, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

8. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid of high specific inductive capacity under pressure in the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, gas-filled chambers, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

9. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid under pressure in the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a pressure exceeding atmospheric pressure, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

10. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid of high specific inductive capacity under pressure in the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a pressure exceeding atmospheric pressure, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

11. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid under pressure in the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a pressure exceeding atmospheric pressure and communicating at their bottoms with the said container, and a plurality

of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

12. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid of high specific inductive capacity under pressure in the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a pressure exceeding atmospheric pressure and communicating at their [illegible] with the said container, the said condensers being connected in series through the medium of the said gaps when the said spark gaps break down.

13. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid under regulable pressure in the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a regulable pressure exceeding atmospheric pressure and communicating with the said container, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

14. A device for generating extremely high potentials, comprising in substance a container, an insulating fluid of high specific inductive capacity under regulable pressure in the said container, and an impulse generator with short discharge period in the said fluid, the said impulse generator comprising a plurality of condensers, a plurality of resistances, a potential source connected in parallel with the said condensers through the medium of the said resistances, chambers filled with gas at a regulable pressure exceeding atmospheric pressure and communicating with the said container, and a plurality of spark gaps in the said chambers, the said condensers being connected in series through the medium of the said spark gaps when the said spark gaps break down.

ARNO BRASCH.
FRITZ LANGE.
MAX DAHL.

Sept. 15, 1925

1,553,364

L. W. CHUBB

MEANS FOR PRODUCING HIGH VOLTAGE

Filed Jan. 20, 1921

Fig. 1.

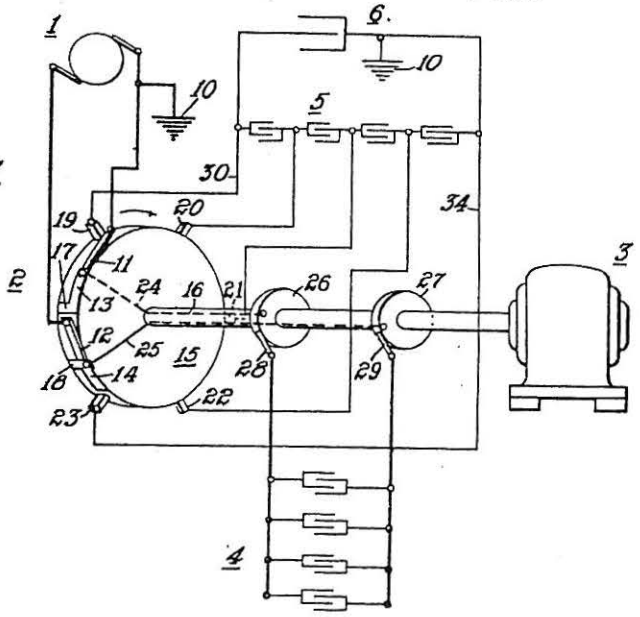


Fig. 2.

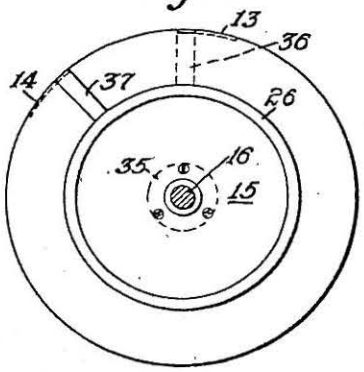


Fig. 3.

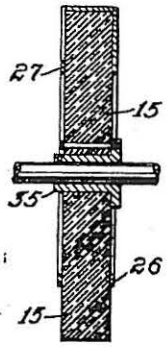
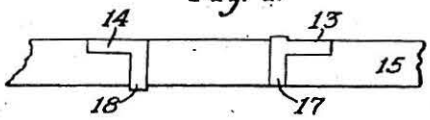


Fig. 4.



WITNESSES:

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W. R. Coley

INVENTOR

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ATTORNEY

Patented Sept. 15, 1925. 1,553,364

UNITED STATES PATENT OFFICE.

LEWIS WARRINGTON CHUBB, OF EDGEWOOD PARK, PENNSYLVANIA, ASSIGNOR TO WESTINGHOUSE ELECTRIC & MANUFACTURING COMPANY, A CORPORATION OF PENNSYLVANIA.

MEANS FOR PRODUCING HIGH VOLTAGE.

Application filed January 20, 1921. Serial No. 438,671.

To all whom it may concern:

Be it known that I, LEWIS WARRINGTON CHUBB, a citizen of the United States, and a resident of Edgewood Park, in the county of Allegheny and State of Pennsylvania, have invented a new and useful Improvement in Means for Producing High Voltages, of which the following is a specification.

My invention relates to means for producing high voltages and it has special relation to the production of high unidirectional voltages, such as are adapted for use in precipitating apparatus, ozonizers, X-ray tubes, radio communication, and the like.

In the prior art, various devices have been proposed embodying a series of condenser units and rotatable charging apparatus therefor, whereby a relatively low initial voltage may be converted to a desirably high value. Such apparatus has been of particular value in connection with precipitating apparatus. However, one side of this type of apparatus is usually grounded and this fact has precluded the permissibility of a ground of either terminal of the initial voltage-generating apparatus. Consequently, such systems have often required considerable maintenance, or have entailed material loss through shut-down.

One object of my invention, therefore, is to provide a method and system of the above-indicated character, wherein the generator apparatus may be permanently grounded without danger to the apparatus and without effecting the reliability thereof.

More specifically stated, it is the object of my invention to provide an energy-storing means of relatively large capacity, such as a bank of parallel-connected condensers, which is intermittently connected to a low-voltage generator, and after disconnection from the generator, the storage means is successively connected to a series of energy-storing and restoring units, such as condensers, whereby the desired high undirectional voltage is secured.

Other and more specific objects of my invention will become evident from the following detailed description, taken in conjunction with the accompanying drawing,

Figure 1 of which is a diagrammatic view of a system organized in accordance with my present invention; and

Figs. 2, 3 and 4 are detailed views, in side elevation in transverse section, and in plan development, respectively, of a preferred form of construction of a portion of the apparatus that is shown in Fig. 1.

Referring to Fig. 1, the system here shown comprises a relatively low-voltage generator 1 of any well-known type, which is associated with a rotatable charging apparatus 2 that is driven by an electric motor 3 for the purpose of charging an energy-storing means of relatively large capacity, such as a bank of parallel-connected condensers 4. A plurality of series-connected energy-storing and restoring units, such as condensers 5, are adapted, through the agency of the charging apparatus 2, to be successively connected to the storage means 4, as subsequently described in detail, to impress and maintain a relatively high undirectional voltage upon any desired consumption circuit, such as a precipitating apparatus 6.

It will be noted that one terminal of the generator 1 and also one terminal of the precipitating apparatus 6, are grounded, as indicated at 10. My present system is designed to permit of this novel arrangement, since the generator 1 is never directly in circuit with the precipitating apparatus 6. On the other hand, the generator 1 charges the storage means 4 and is then disconnected therefrom before the storage means successively discharges portions of its energy into the series-connected condenser units 5. Consequently, although the storage means 4 must be insulated from ground, the cost of such construction, compared with the cost of suitably insulating all coils and other parts of the generator from ground, is comparatively small, and I am thus enabled to provide a relatively inexpensive, although thoroughly reliable, system of the class set forth.

The rotatable charging apparatus 2 is diagrammatically illustrated as comprising a plurality of brushes 11 and 12 which are respectively connected to the terminals of the generator 1 and bear upon elongated contact segments 13 and 14 which are located near one peripheral edge of a rotatable disk

or cylinder 15 of insulating material. The disk 15 is rigidly mounted upon a suitable shaft 16 which, in turn, is directly, or otherwise suitably, coupled to the driving electric motor 3.

The contact segments 13 and 14 are provided, at their confronting ends, with laterally projecting lugs or ears 17 and 18, respectively, for the purpose of engaging, in pairs, a plurality of suitable brushes or terminal members 19 to 23, inclusive. These brushes are equally spaced around the periphery of the disk 15, with the exception that an arcuate distance of double the length between brushes, such as 19 and 20, is left between the brushes 23 and 19, whereby the generator-connected brushes 11 and 12 may suitably function, as hereinafter described in detail.

Although I have illustrated only five delivery brushes 19 to 23, inclusive, for connection to a series of four condenser units designated at 5, it will be understood that any suitable number of brushes and a corresponding number of condenser units may be employed to obtain any desired high voltage.

In the event of employing the illustrated five delivery brushes, the spacing thereof is substantially 60 degrees apart, 120 degrees being left between the brushes 19 and 23, as previously mentioned. The portions 17 and 18 of the rotatable contact segments 13 and 14 are thus also located substantially 60 degrees apart, whereby the two portions 17 and 18 may successively engage the pairs of brushes 19 and 20, 20 and 21, etc. The generator-connected brushes 11 and 12 bear upon the elongated contact segments 13 and 14, whereby a relatively long period of time is allowed for the complete charging of the storage means 4. Since the elongated contact segments 13 and 14 are located near one edge of the disk 16, while the lateral portions 17 and 18 are located near the other edge of the disk, there is no interference between the delivery brushes 19 to 23, inclusive, and the elongated segments 13 and 14.

For the purpose of connecting the contact segments 13 and 14 to the storage means 4, a plurality of suitable conductors 24 and 25 are connected to slip-rings 26 and 27, respectively, that are rigidly mounted upon, and insulated from, the driving shaft 16. Suitable brushes 28 and 29 bear upon the slip-rings 26 and 27 and are connected to the terminals of the circuit including the parallel-connected condensers 4.

The initial delivery brush 19 is connected, through conductor 30, to the common left-hand terminal of the series condenser circuit 5 and of the precipitation apparatus 6, while the last delivery brush 23 is connected, through conductor 34, to the remaining terminals of the two sets of apparatus. The intervening brushes 20, 21 and 22 are connected to points intermediate the respective pairs of condenser units 5.

The operation of my system may be briefly set forth as follows, rotation being considered as clockwise, as indicated by the arrow: Upon initial connection of the brushes 11 and 12 to the contact segments 13 and 14, as illustrated, energy from the generator 1 is transferred, through the slip-rings 26 and 27, to the storage means 4, and the charging operation continues for a relatively long period, depending upon the selected length of the contact segments 13 and 14. The storage means 4 is thus as heavily charged as may be desired.

After the brushes 11 and 12 have become disengaged from the contact segments 13 and 14, so that the generator 1 is no longer connected in circuit, the segment portions 17 and 18 come into contact with the brushes 19 and 20 to connect the left-hand condenser unit 5 to the storage means 4 for a short period of time. The segment portions 17 and 18 then pass on to subsequently engage the brushes 20 and 21, whereby the second condenser unit 5 in the series is charged. This operation is repeated until all condenser units of the set 5 are fully charged to maintain the desired high unidirectional voltage upon the precipitation apparatus 6. The contact segments 13 and 14 then again come into contact with the generator-connected brushes 11 and 12, whereby another charge is supplied to the storage means 4, which charge is consecutively distributed over the condenser units 5.

The desired high voltage may thus be maintained by reason of the continuous charging and discharging operations of the storage means 4, and such operations are maintained without any danger by reason of the permanent grounding of both the generator and the precipitator circuit.

Figs. 2, 3 and 4 provide a more accurate idea of the preferred relatively compact form of the rotative charging apparatus 2. The insulating disk 15 is provided with a central hub or sleeve 35 which may be rigidly secured to the driving shaft 16. The elongated contact segments 13 and 14 may be directly connected, by end-face strips 36 and 37, to annular members or rings 26 and 27 that are located on the opposite sides or faces of the disk 15, these rings serving as slip-rings upon which the brushes 28 and 29 may bear. In this way, a relatively compact and reliable structure is provided.

It will be seen that, by my invention, the production of a relatively high unidirectional voltage is maintained by employing a charging generator, a series of energy-storing and restoring units that are connected across the precipitating apparatus, and an intervening storage means of high capacity

which is alternately charged from the generator and fractionally discharged into the circuit comprising the series-connected condenser units 5. By this construction, permanent grounds of both the generator and the precipitating circuits may be maintained without affecting the operation of the system and to secure the previously-mentioned other advantages.

It should be noted that, while I have shown my apparatus in a simplified form for the sake of clearness, in practice it may be advisable to reduce the brush friction load and thus decrease the necessary size of the driving motor 3.

The only brushes bearing on the periphery of the large disk 15 will be those corresponding to the energy-storing device 4. All other brushes will make contact with slip-rings of relatively small diameter mounted on the shaft 16, thus materially reducing the driving friction in case a large number of condenser units 5 and corresponding brushes are used. The necessary electrical connections will be made by means of conductors, connected between the various slip-rings and suitable contact segments on the periphery of the disk 15 for co-operating with the brushes corresponding to the device 4.

Furthermore, by employing the arrangement shown in my copending application, Serial No. 428,984, filed Dec. 7, 1920, it is possible to use an alternating-current source of energy in lieu of the illustrated generator 1.

I do not wish to be restricted to the specific circuit connections, structural details, or arrangement of parts herein set forth, as various modifications thereof may be made without departing from the spirit and scope of my invention. I desire, therefore, that only such limitations shall be imposed as are indicated in the appended claims.

I claim as my invention:

1. The combination with a low-voltage source and a high-voltage unidirectional consumption device, of a plurality of energy-storing and restoring units connected in series relation, a rotatable member, a plurality of terminal members connected between said units and located near one side of said rotatable member, a plurality of contact members connected to the terminals of said source and located near the other side of said rotatable member, a plurality of segments having portions adapted for engaging said contact members and subsequently engaging adjacent pairs of said terminal members, an energy-storing device, and a plurality of slip-rings for connecting the respective segments to the terminals of said energy-storing device.

2. The combination with a low-voltage source and a high-voltage unidirectional consumption device, of a plurality of energy-storing and restoring units connected in series relation, a rotatable member, a plurality of terminal members connected between said units and located near one side of said rotatable member, a plurality of contact members connected to the terminals of said source and located near the other side of said rotatable member, a plurality of segments having elongated portions adapted for engaging said contact members and relatively short portions for subsequently engaging adjacent pairs of said terminal members, an energy-storing device comprising a plurality of parallel-connected elements, and a plurality of slip-rings for connecting the respective segments to the terminals of said energy-storing device.

3. The combination with a low-voltage source and a high-voltage unidirectional consumption device, of a plurality of energy-storing and restoring units connected in series relation, a rotatable member, a plurality of terminal members connected between said units and located near one side of said rotatable member, a plurality of contact members connected to the terminals of said source and located near the other side of said rotatable member, a plurality of segments having portions adapted for engaging said contact members and subsequently engaging adjacent pairs of said terminal members, an energy-storing device, a plurality of slip-rings for connecting the respective segments to the terminals of said energy-storing device, and means for grounding one terminal of said source, and one terminal of the series circuit of said units.

In testimony whereof, I have hereunto subscribed my name this 11th day of January 1921.

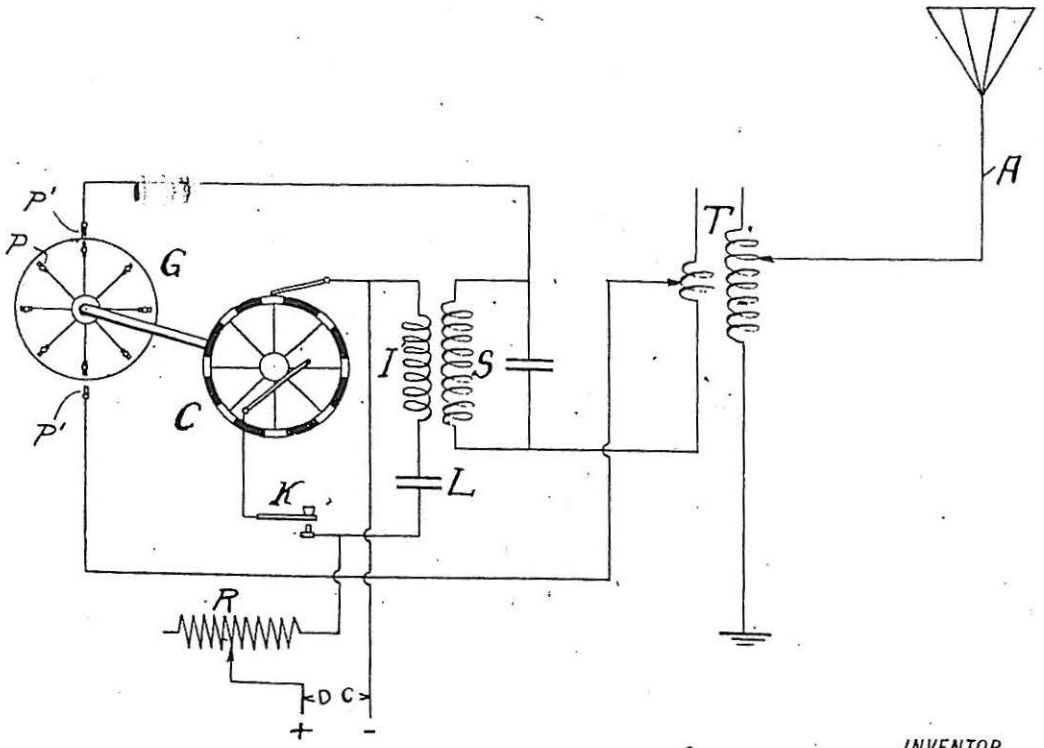
LEWIS WARRINGTON CHUBB.

W. S. LEMMON.

RESONANT CONVERTER.

APPLICATION FILED SEPT. 1, 1916.

1,340,963. Patented May 25, 1920.



INVENTOR

Walter S. Lemmon

BY

Pennie Davis & Marvin

ATTORNEYS

UNITED STATES PATENT OFFICE.

WALTER S. LEMMON, OF NEW YORK, N. Y.

RESONANT CONVERTER.

1,340,963. Specification of Letters Patent. Patented May 25, 1920.

Application filed September 1, 1916. Serial No. 117,993.

To all whom it may concern.

Be it known that I, WALTER S. LEMMON, residing in the city, county, and State of New York, have invented certain new and useful Improvements in Resonant Converters: and I do hereby declare the following to be a full, clear, and exact description of the invention, such as will enable others skilled in the art to which it appertains to make and use the same.

The object of this invention is to provide a simple and inexpensive apparatus for the production of oscillations in radio signaling systems. The arrangement contemplated is particularly adapted to produce oscillations of a remarkably uniform character which, when received by means of the ordinary radio receiving set including a telephone receiver, will produce in the telephone receiver a pure and easily distinguished musical tone.

The nature of the invention will be understood from the accompanying drawing, illustrating an embodiment and from the following description.

In this drawing: The figure represents an arrangement of sending circuits of a radio signaling system, in which a synchronous spark gap and an associated rotary controller are used; the rotary controller serving to make and break a direct current circuit.

In the arrangement of the figure the source of continuous current indicated by the letters DC is connected through an adjustable resistance R (whose function is to limit and control the supplied energy) to an oscillatory circuit containing the rotary circuit controller C, inductance I, which is the primary of a transformer, and the condenser L. It will be observed that the direct current source is so connected to the oscillatory circuit as to apply the direct current energy to two circuits, one of which contains the circuit controller C and the other of which contains the inductance and capacity. In other words, the oscillatory circuit is, in its relation to the direct current source, made up of two parallel paths, one of which containing the inductance and capacity is capable of absorbing energy from the direct current source when the direct current through the rotary controller is interrupted; and the other of which affords a very low resistance path for the direct current when the circuit through the controller is closed, which path also provides a short circuit for the oscillatory circuit.

With the parts thus arranged, a rotation of the controller will periodically interrupt one parallel path causing the direct current to be shunted into the other parallel path containing the inductance and capacity, thereby storing energy in this portion of the circuit. When the controller brush has passed over the insulation segment and comes upon the next conducting segment, the closed circuit is completed and this stored energy will discharge itself through the closed circuit, and if the circuit through the controller remained closed, would, because of the inductance and capacity in the circuit, give rise to damped electrical oscillations. If, however, the speed of rotation and the design of the controller is such, that the circuit is made and broken at intervals which corresponds substantially to the natural frequency of the oscillatory circuit, then the change of circuit connections will be effected substantially without sparking and an alternating current of constant amplitude will flow in the transformer primary I. Consequently, energy in the form of a constant amplitude alternating current may be taken from the circuit through the instrumentality of the transformer secondary S, which may be included in the ordinary spark gap circuit of a radio signaling system.

The closed resonant circuit contains a telegraph key K, and the secondary S is included in the spark gap circuit which is inductively associated through the transformer T with the antenna A. In this case, a synchronous spark gap is used in the spark gap circuit. This apparatus may have any well known form, and should be driven in synchronism with the circuit controller C. By way of example, I have shown a rotating disk G mounted on the same axle with the controller C and carrying radially arranged spark points coöperating with two fixed spark points located at extremities of a diameter of the disk. The rotating disk G may have the same number of spark points as the rotating controller C has pairs of segments and hence where these two devices rotate at the same speed, only alternating half waves of the alternating current are used for sparking. In practice it is, under certain circumstances, desirable that both half waves of the alternating current be utilized,

thereby producing two sparks per cycle, and this can obviously be effected in the apparatus by doubling the number of spark points on the disk G or by rotating the disk G at double the speed of the controller C.

Although the primary purpose of the invention is, as above set forth, to produce from a direct current an alternating current of constant amplitude by supplying energy in the form for a direct current to the resonant circuit and permitting the stored energy to oscillate in the said circuit in substantial synchronism with the natural frequency of the circuit, particularly for radio signaling purposes, nevertheless it is possible to supply the energy to the resonant circuit in the form of an alternating current and permit the stored energy to discharge itself as before, and I consider such an arrangement within the broad scope of my invention.

What I claim is:

1. Apparatus for the production of electrical oscillations comprising a source of electrical energy, an oscillatory circuit, means for alternately connecting and disconnecting said circuit to said source, a second oscillatory circuit coupled to said first circuit and a spark gap connected to said second circuit adapted to discharge the energy transferred to the second circuit at time intervals corresponding to the alternate connection and disconnection of the first circuit to the electrical source.

2. Apparatus for the production of electrical oscillations comprising a source of electrical energy, an oscillatory circuit, means for alternately connecting and disconnecting said oscillatory circuit to said source at a frequency corresponding to the natural frequency of said circuit, a second oscillatory circuit coupled to said first circuit and a spark gap connected to said second circuit adapted to discharge the energy induced in said second circuit synchronously with said connecting and disconnecting means.

3. Apparatus for the production of electrical oscillations comprising a source of direct current, an oscillatory circuit, means for periodically charging said circuit from said source at a frequency corresponding to the natural frequency of said circuit, a second oscillatory circuit coupled to said first circuit, and a spark gap connected to said second circuit adapted to discharge the energy transferred to said second circuit synchronously with said periodic charging means.

4. Apparatus for the production of high frequency electrical oscillations comprising a source of direct current, an oscillatory circuit, a rotary multisegment controller adapted to periodically connect said circuit to said source, a second oscillatory circuit coupled to said first circuit, and a rotary spark gap connected to said second circuit adapted to synchronously operate with said controller and to discharge the energy transferred to said second circuit.

5. Apparatus for the production of high frequency electrical oscillations comprising a source of direct current, an oscillatory circuit, a rotary multisegment controller adapted to periodically connect said circuit to said source and to periodically discharge said circuit at a frequency corresponding to the natural frequency of said circuit, a second oscillatory circuit coupled to said first circuit and a rotary spark gap connected to said second circuit adapted to rotate synchronously with said controller and to discharge said second circuit.

In testimony whereof I affix my signature.

WALTER S. LEMMON.

Sept 15, 1925 1,553,363

L. W. CHUBB

MEANS FOR PRODUCING HIGH VOLTAGE

Filed Dec. 7, 1920

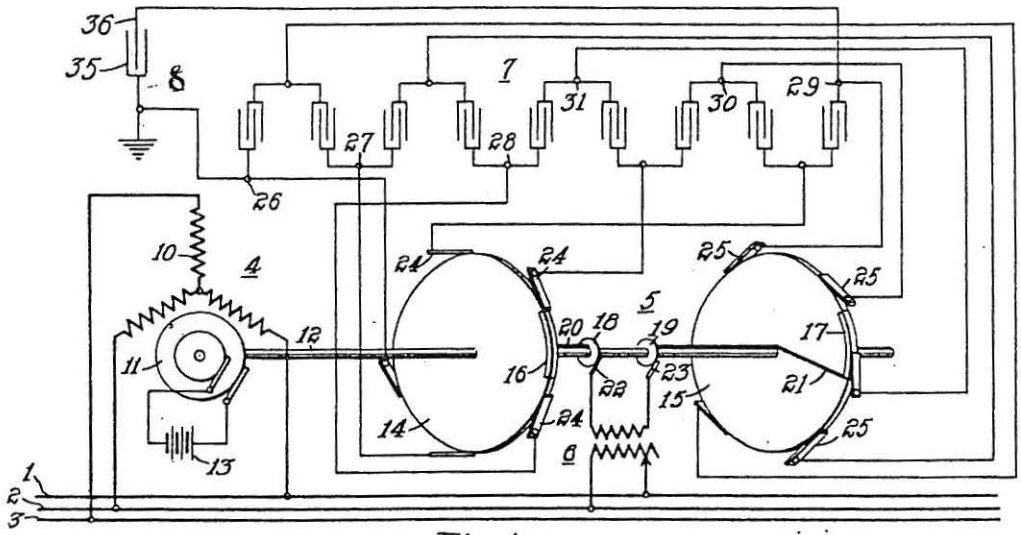


Fig. 1.

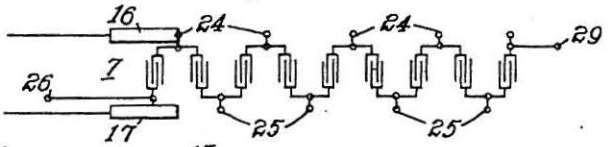


Fig. 2.

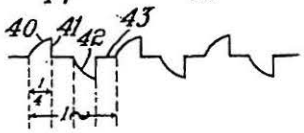


Fig. 3.

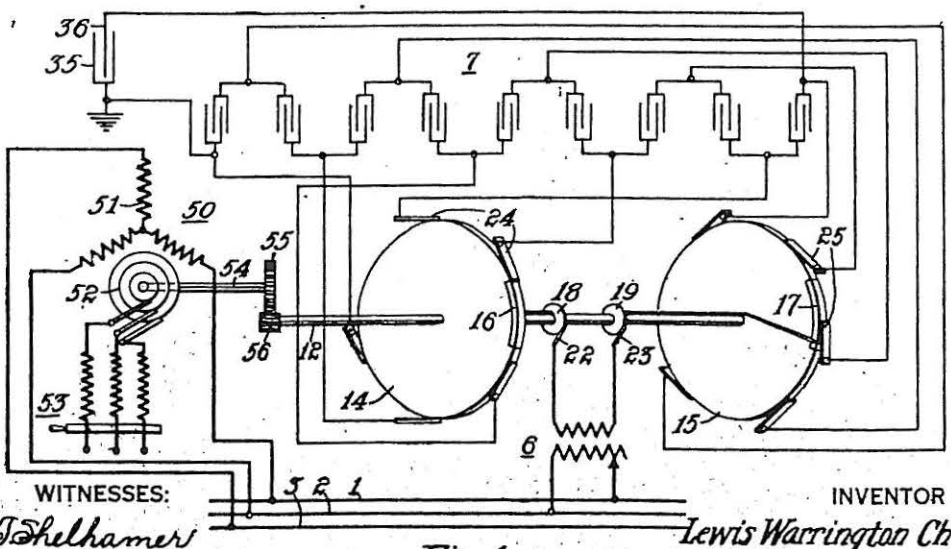


Fig. 4.

WITNESSES:

H. J. Shelhamer

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INVENTOR

Lewis Warrington Chubb

BY

Wesley G. Carr

ATTORNEY

Patented Sept. 15, 1925. 1,553,363

UNITED STATES PATENT OFFICE.

LEWIS WARRINGTON CHUBB, OF EDGEWOOD PARK, PENNSYLVANIA, ASSIGNOR TO WESTINGHOUSE ELECTRIC & MANUFACTURING COMPANY, A CORPORATION OF PENNSYLVANIA.

MEANS FOR PRODUCING HIGH VOLTAGE.

Application filed December 7, 1920. Serial No. 428,984.

To all whom it may concern:

Be it known that I, LEWIS WARRINGTON CHUBB, a citizen of the United States, and a resident of Edgewood Park, in the county of Allegheny and State of Pennsylvania, have invented a new and useful Improvement in Means for Producing High Voltage, of which the following is a specification.

My invention relates to means for producing high voltage and it has special relation to the production of high unidirectional voltages, such as are adapted for use in precipitating apparatus, ozonizers, X-ray tubes, radio communication and the like.

In the prior art, various apparatus has been devised employing direct-current energization, whereby a plurality of energy-storing-and-restoring units, such as condensers connected in series relation, have been successively charged and have been subsequently discharged. However, so far as I am aware, no alternating-current apparatus of this type has been devised.

One object of my invention, therefore, is to provide an apparatus of the above-indicated character, which shall employ alternating-current energization, whereby, through the use of a step-up transformer, higher direct-current voltages than have previously been available may readily be secured.

Another object of my invention is to provide means of the class in question for supplying energy that is derived from a low-voltage source of fixed frequency to a series of energy-storing-and-restoring units at any desired frequency.

Other and more specific objects of my invention will become evident from the following detailed description taken in conjunction with the accompanying drawings wherein—

Figure 1 is a diagrammatic view of a system, and apparatus organized and constructed in accordance with one form of my invention;

Fig. 2 is a diagrammatic view in development of a portion of the system that is shown in Fig. 1;

Fig. 3 is a curve chart illustrating the type of voltage curve that is supplied to the series of condensers by my apparatus; and

Fig. 4 is a diagrammatic view of a modified form of my invention.

Referring to Fig. 1, the system here shown comprises a suitable alternating-current circuit, which is preferably of the three-phase type comprising conductors 1, 2 and 3 for supplying energy to a synchronous motor 4. The motor 4 is adapted to drive a rotative charging apparatus 5, which derives its energy from the supply circuit conductors 1 and 2, for example, by means of a step-up transformer 6. A set of energy-storing-and-restoring units 7, here shown, for purposes of illustration, as condensers, are connected in series relation with a consumption device 8, which may be, for example, an electric precipitator.

The synchronous motor 4 comprises a three-phase primary winding, or stator 10 and a co-operating field winding, or rotor 11, which is mounted upon a driving shaft 12. A suitable source of direct-current energy, such as a battery 13, is provided for energizing the field winding 11, in accordance with customary practice. The synchronous motor 4, in the particular case illustrated, is of the twelve-pole type to provide the proper speed for the rotative charging apparatus 5, as subsequently explained in detail.

The apparatus 5 is shown as comprising a pair of discs, or cylinders 14 and 15 of insulating material, which are rigidly fastened to the driving shaft 12 and are respectively provided with contact segments 16 and 17 that cover a predetermined fraction of their circumference. A plurality of suitably insulated slip-rings 18 and 19 are rigidly mounted upon the shaft 12 intermediate the discs 14 and 15 and are respectively connected to the contact segments 16 and 17 by means of conductors 20 and 21.

The transformer 6 may be adapted to provide any desired multiplication of the supply-circuit voltage by suitable variation of its primary-winding connections, as will be

readily understood. The secondary winding of the transformer is connected, through suitable brushes 22 and 23, to the slip-rings 18 and 19, whereby the rotatable contact segments 16 and 17 are respectively connected to the opposite terminals of the transformer winding.

A plurality of brushes or control fingers 24 are spaced around the rotatable disc 14, while corresponding brushes 25 are located, in staggered relation to the brushes 24, around the circumference of the other rotatable disc 15.

In the illustrated case, five brushes 24 are provided, being spaced apart approximately one-sixth of the circumference of the disc 14, thus leaving a relatively long space between two of the brushes that respectively correspond to the opposite ends of the series-connected set of condensers 7.

The contact segment 16 is of a length approximately three-fourths of the arcuate distance between the successive brushes 24, that is, three-fourths times one-sixth, or approximately one-eighth of the circumference of the disc 14. The purpose of this particular proportion of parts will become evident from the subsequent description.

It will be understood that any desired number of condensers 7 may be employed, depending upon the voltage transformation that is required between the secondary winding of the transformer 6 and the high-voltage delivery circuit. The number of brushes in the rotatable charging apparatus 5 will, of course, vary in accordance with the number of condenser units that are employed.

One of the brushes 24 is connected directly to one end of the series condenser circuit, that is to say, to one terminal conductor 26 of the high-voltage circuit. The remaining brushes, taken in a counter-clockwise direction, are connected between the second and third condenser units, the fourth and fifth condenser units, etc., as indicated by the tap-points 27 and 28.

The equal number of brushes 25 for the disc 15 are arranged in a complementary manner, that is, one brush 25 is connected to the right-hand terminal of the condenser circuit, that is, to the terminal conductor 29 of the high-voltage circuit, while the remaining brushes, taken in a clockwise direction, are connected between the eighth and seventh condenser units, the sixth and fifth condenser units, etc., as indicated by the tap-points 30 and 31, for example.

As previously stated, the high unidirectional voltage that is delivered to the terminal conductors 26 and 29 may be employed in connection with a precipitation device, such as that illustrated at 8, comprising a grounded electrode 35 and a second co-operating electrode 36.

In the illustrated case the rotative charging apparatus, by reason of the number and spacing of the contact brushes, is rotated at one-sixth of the two-pole synchronous speed. In other words, a twelve-pole synchronous motor 4 will provide the desired speed of operation. The developed view of Fig. 2 and the corresponding curve chart, Fig. 3, will serve to make clear the sequence of operation during the charging of the condenser units 7.

In the position shown in Fig. 2, contact segment 16 begins contact with the first brush 24 at the instant that the alternating-current voltage in the secondary winding of the transformer 6 is zero, as indicated by the curve or graph in Fig. 3. This contact continues for approximately one-fourth of a cycle, by reason of the above-described proportion of parts and rotative speed of the charging apparatus, at which time the first, or left-hand, condenser 7 in Fig. 2, is charged to the peak value of the voltage, as indicated by the portion 40 of the curve in Fig. 3. At this instant the contact segment 16 leaves the first brush 24 and the circuit is open for one-fourth of a cycle, as indicated by the straight line portion 41 of the curve in Fig. 3.

The next contact thus begins at zero voltage when the other contact segment 17 engages the second brush 25. This contact continues until an effective maximum voltage value is obtained, as indicated by curve portion 42, to charge the second condenser 7 in the opposite direction. Another open-circuit then obtains for one-quarter of a cycle, as indicated by portion 43 of the graph.

The actions just described are repeated as the rotative charging apparatus is operated until all of the condensers 7 have been successively charged. It will be noted that, by reason of the particular connections of the condenser units 7 with respect to the contact segment 17 and the corresponding brushes, the condenser units are cumulatively charged, although the voltage peaks, as indicated in Fig. 3, are alternately positive and negative. Consequently, the total or cumulative effect of all the condenser voltages is adapted to be discharged through the high-voltage terminal conductors 26 and 29.

In this way, a relatively low-voltage alternating-current circuit may have its voltage transformed to any desired relatively high value and this increased voltage is successively applied to a series-related set of condenser units to ultimately produce very high unidirectional voltage for the desired purpose. By reason of the continuous repeating effect of the rotative charging apparatus 5, this high voltage is continuously supplied to the consumption device 8. This effect is particularly desirable in the case of

treatment of gases containing valuable elements to be salvaged by precipitation, as will be understood.

Referring to Fig. 4, the apparatus here shown comprises the supply circuits, my rotatable charging apparatus 5, the step-up transformer 6, the series of energy-storing-and-restoring units 7 and the consumption device 8, as previously described.

However, to provide a desirable speed regulation of the charging apparatus 5, an induction motor 50 is provided for driving the shaft 12. The induction motor 50 comprises a three-phase, twelve-pole primary winding, or stator 51 and a wound rotor 52, with which is associated a suitable polyphase variable resistor 53 for speed-regulating purposes, in accordance with a familiar practice.

The rotor 52 is rigidly mounted upon a shaft 54, to one end of which a gear-wheel 55 is secured to mesh with a pinion 56 that is mounted upon the driving shaft 12. The ratio between the speeds of the gear-wheel 55 and the pinion 56 may be two to one, for example, if it is desired to vary the speed of the rotative charging apparatus from zero to approximately twice the synchronous speed that is obtained by the apparatus shown in Fig. 1.

It will be understood, however, that any other desired ratio, or, in fact, any other means for effecting the desired speed regulation of the driving shaft 12, may be employed.

The present apparatus is adapted to deliver a variable frequency to the set of condenser units 7. By adjusting the amount of active secondary resistance 53, the speed of the driving shaft 12 may be regulated, as desired, between zero and the above-mentioned synchronous speed. Such regulation results in making and breaking the contact between the contact segments 16 and 17 and the corresponding sets of brushes 24 and 25 at progressively different points in the voltage wave. Consequently, the series of condenser units will be supplied with a terminal voltage of a frequency corresponding to that of the driving shaft 12; that is, a frequency varying inversely with the degree of slip of the induction motor 50.

I do not wish to be restricted to the specific circuit connections, structural details, or arrangement of parts herein set forth, as various modifications may be made therein without departing from the spirit and scope of my invention. I desire, therefore, that only such limitations shall be imposed as are indicated in the appended claims.

I claim as my invention:

1. The combination with a low-voltage source of alternating-current and a high-voltage unidirectional consumption device, of a plurality of energy-storing and restoring units connected in series relation, a plurality of sets of contact members disposed in staggered relation with respect to each other, means for connecting said members between successive pairs of said energy-storing units, a plurality of alined and simultaneously operating contact segments for successively engaging the respective members of each set, and a plurality of slip-rings for connecting said segments to the respective terminals of said source.

2. The combination with a low-voltage source of alternating-current and a high-voltage unidirectional consumption device, of a plurality of energy-storing and restoring units connected in series relation, a plurality of sets of stationary contact members, said sets having their members connected between successive pairs of said energy-storing units, a plurality of contact segments for the respective sets, each segment being approximately equal to ¾ of the distance between said contact members, and means for connecting said segments to the respective terminals of said alternating-current source.

3. The combination with a low-voltage source of alternating-current and a high-voltage unidirectional consumption device, of a plurality of energy-storing and restoring units connected in series relation; a plurality of sets of stationary contact members, said sets having their members connected between successive pairs of said energy-storing units and disposed in staggered relation, a plurality of rigidly associated contact segments for the respective sets, each segment being approximately equal to ¾ of the distance between said contact members, a plurality of slip-rings for connecting said segments to the respective terminals of said source, and means for operating said segment at a predetermined speed.

In testimony whereof I have hereunto subscribed my name this 30th day of November, 1920.

LEWIS WARRINGTON CHUBB.

March 22, 1932. H. E. REDEKER 1,850,689

OSCILLATION GENERATOR PROCESS AND APPARATUS

Filed Aug. 13, 1928

FIG_1_

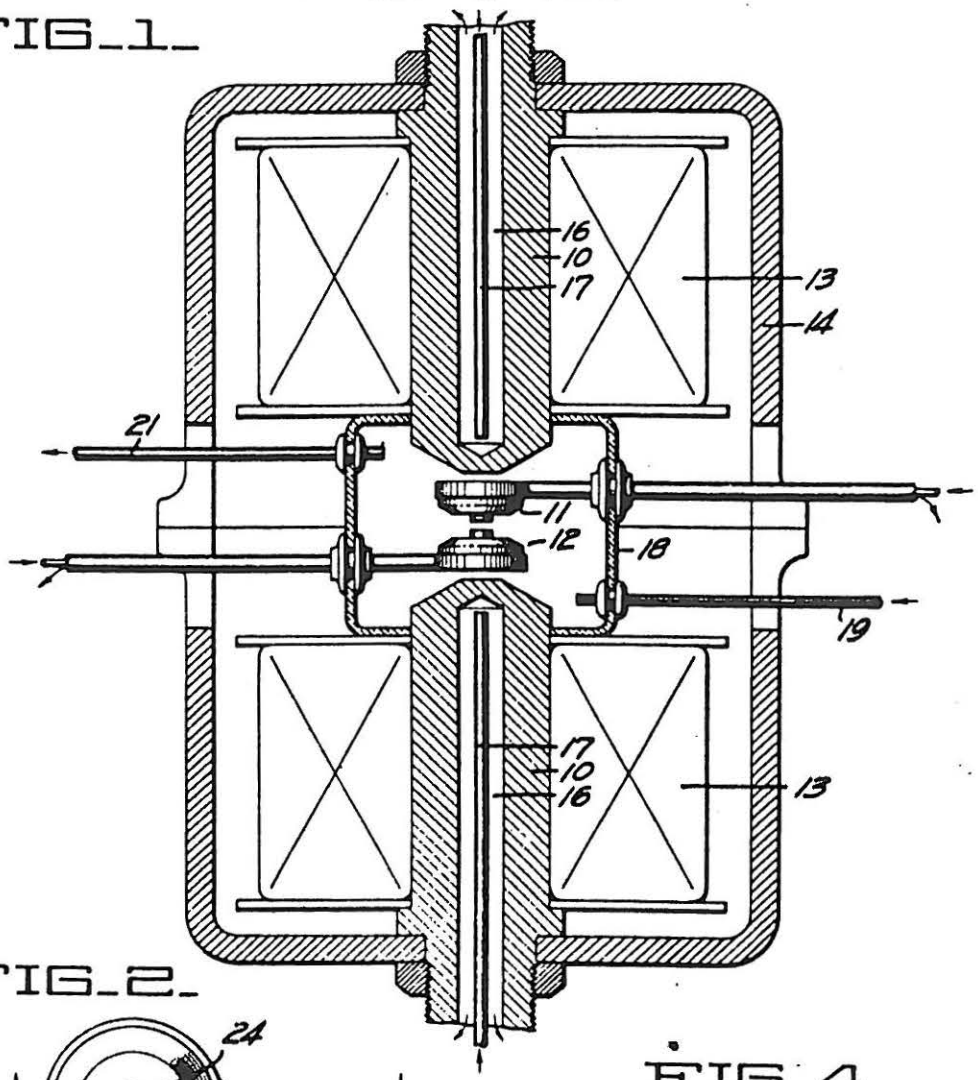
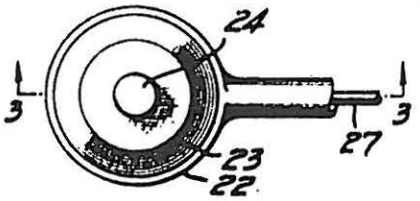


FIG_2_



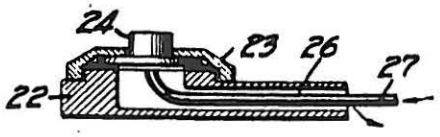
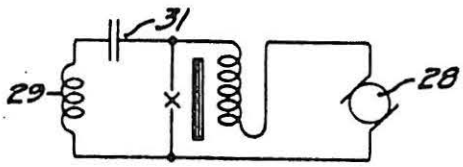


FIG_3_

FIG_4_



INVENTOR.
Harry E. Redeker
BY White, Prat & Fryer
ATTORNEYS.

Patented Mar. 22, 1932 1,850,689

UNITED STATES PATENT OFFICE

HARRY E. REDEKER, OF PALO ALTO, CALIFORNIA, ASSIGNOR TO FEDERAL TELEGRAPH COMPANY, OF SAN FRANCISCO, CALIFORNIA, A CORPORATION OF CALIFORNIA

OSCILLATION GENERATOR PROCESS AND APPARATUS

Application filed August 13, 1928. Serial No. 299,245.

This invention relates to the generation of high frequency waves by oscillating arcs and has as its object to increase the frequency of operation of such devices.

In the past it has been common to utilize arc converters for the generation of high frequency oscillations utilized in radio signaling apparatus. Prior to my invention, however, it has to the best of my knowledge, been considered impossible to operate arc converters stably upon frequencies less than 1000 meters.

Heretofore it has been considered essential to the stable operation of an arc converter, to have the element of carbon present either by utilizing electrodes containing carbon or by supplying carbon in the enveloping atmosphere. Apparently the carbon ionizes and influences operation of the arc. In my experiments with arc converters, I have made the discovery that as long as the element carbon is supplied to an arc converter in appreciable quantities, the converter cannot be operated successfully under a given minimum wave length, which generally is in the neighborhood of 1000 meters.

The frequency at which a converter can oscillate is theoretically determined by the rate at which the arc will scavenge itself. Stated in another way, it is dependent upon the rate at which the path between the electrodes can de-ionize itself to interrupt flow of the current from the exciting source. As a result of my discoveries, I have determined that it is impossible to appreciably increase the rate at which the ionized path can be de-ionized, as long as the element carbon is present, since the effect of carbon is apparently predominant over that of any other element which can be supplied. I have also discovered that by eliminating carbon from the arc and introducing certain other elements it is possible to operate upon relatively short wave lengths. The preferred elements are those which are radio active such as thorium and uranium.

Referring to the drawings:

Figure 1 is a side elevational view in cross section illustrating one form of apparatus designed for carrying out the invention.

Fig. 2 is a plan view of a portion of one of the electrodes employed in the apparatus of Fig. 1.

Fig. 3 is a cross sectional view taken along the line 3—3 of Fig. 2.

Fig. 4 is a circuit diagram illustrating the manner in which the arc is connected with an oscillation circuit.

In Fig. 1 I have shown an arc converter of the longitudinal magnetic field type comprising a pair of magnetic pole pieces 10 between which are disposed the anode and cathode, 11 and 12, respectively. Pole pieces 10 are provided with the usual windings 13, and are mounted upon a structure 14 for completing the magnetic field. To provide for adequate cooling, pole pieces 10 are preferably provided with passageway 16 within which tubes 17 extend, whereby cooling fluid can be introduced into tubes 17 and discharged from passages 16. The electrodes are preferably enclosed within a chamber 18 which is sealed to enable the atmosphere about the electrodes to be controlled. Vessel 18 is tapped by tubes 19 and 21 for the introduction and removal of gases.

The electrodes may be formed in a variety of ways, providing the use of carbon, either alone or combined, is avoided. Since certain elements which I have found to be effective are relatively expensive, and since a relatively small quantity of such an element will suffice for the purposes of my invention, I prefer to form the main body of the electrodes of some good conductor of electricity, such as copper, and make provision for attaching thereto small quantities of the desired element. I have secured good results by utilizing copper electrodes and supplying the additional element to the cathode in the form of a powder. For example I can provide the face of the cathode with a small depression or cavity within which the powdered substance is introduced. A more convenient way to supply the additional element however is to form a cathode as shown in Figs. 2 and 3. In this case I provide a copper body 22 upon which is threaded a ferrule 23. Clamped in position upon the body 22 by ferrule 23, is a small tip 24 which contains the additional element which I supply. Both

electrodes are preferably cooled by a suitable fluid, and for this purpose I have shown passages 26 within which the tubes 27 extend for introduction of a cooling fluid.

With respect to the elements that can be employed for the generation of oscillations of relatively low wave lengths, I have discovered that the elements titanium, zirconium, thorium and uranium are each effective to secure the results of my invention. These materials are preferably utilized in powdered form and the particular element to be employed is mixed with a suitable binder and compressed to form the tip 24. The composition of the tip should be such as to render it conductive.

The atmosphere within which the arc is enveloped is preferably of an inert gas, such as hydrogen. The air or other active gases within the chamber are preferably exhausted thru tube 21 and hydrogen introduced thru tube 19. By means of suitable apparatus well known in the prior art, I maintain the hydrogen atmosphere within chamber 18 at a comparatively constant pressure, preferably below atmospheric.

In Fig. 4 I have shown a conventional form of oscillation circuit associated with my arc converter. In this case the electrodes are supplied with current from a suitable source such as the direct current generator 28, while the oscillation circuit connected across the electrodes consists of series connected inductance and capacitance 29 and 31.

When the arc converter described above is in operation, the longitudinal magnetic field causes the arc formed between the electrodes to gyrate about an axis corresponding to the axis of the magnetic field. I have found that this arrangement is particularly adapted for the production of short wave lengths when the arc is being supplied with one of the elements mentioned above. When the arc is being supplied with the element titanium, the converter operates stably upon wave lengths of from 400 to 500 meters. By a spectrum analysis, I determined that the titanium which I employed contained traces of hafnium. When supplying the element zirconium in the absence of other elements, except of course the copper of the electrodes, the arc operated upon wave lengths of from 200 to 400 meters, and with the element thorium the arc operated upon wave lengths of from 150 to 350 meters. Best results were obtained however by supplying the element uranium which made possible operation of the arc upon wave lengths as low as 70 meters, although the arc operated best upon wave lengths of from 125 to 250 meters. It will be noted that titanium, zirconium, thorium and uranium are nearly electrically neutral in that they are situated near the center of the periodic table. Although all of the elements stated enabled operation of the arc upon shorter wave lengths than has heretofore been possible, the results obtained by supplying uranium were exceptionally remarkable and unexpected.

Insofar as my observations up to the present date are concerned, I have been unable to make my converter operate upon short wave lengths when the element carbon is present in appreciable quantities. Thus if the inert hydrogen atmosphere is replaced by an atmosphere of a hydrocarbon, such as alcohol vapor, the arc will no longer operate upon short wave lengths, and the supplying of additional elements, as for example uranium, appear to have practically no effect upon the arc.

When it is desired to operate the arc upon the shortest possible wave lengths, the size and positioning of the electrodes should be such as to provide a minimum amount of capacitance between the electrodes.

I claim:

1. In an oscillation generator comprising as the source of oscillations an electric arc, the method of increasing the frequency of operation of said arc which comprises eliminating carbon from the arc and supplying thereto a radio active substance.

2. In an oscillation generator comprising as the source of oscillations an electric arc, the method of increasing the frequency of operation of said arc which comprises eliminating carbon from the arc and supplying uranium thereto.

3. In an oscillation generator comprising as the source of oscillations an electric arc in a longitudinal, magnetic field, the method of increasing the frequency of operation of said arc which comprises eliminating carbon from the arc and supplying uranium thereto.

4. An arc oscillation generator having a cathode comprising a radio active substance, together with another substance in a carbon free atmosphere, the second substance alone being incapable of producing an oscillating arc.

5. An arc oscillation generator having a cathode comprising a radio active substance and copper, said cathode operating in a carbon free atmosphere.

In testimony whereof, I have hereunto set my hand.

HARRY E. REDEKER.

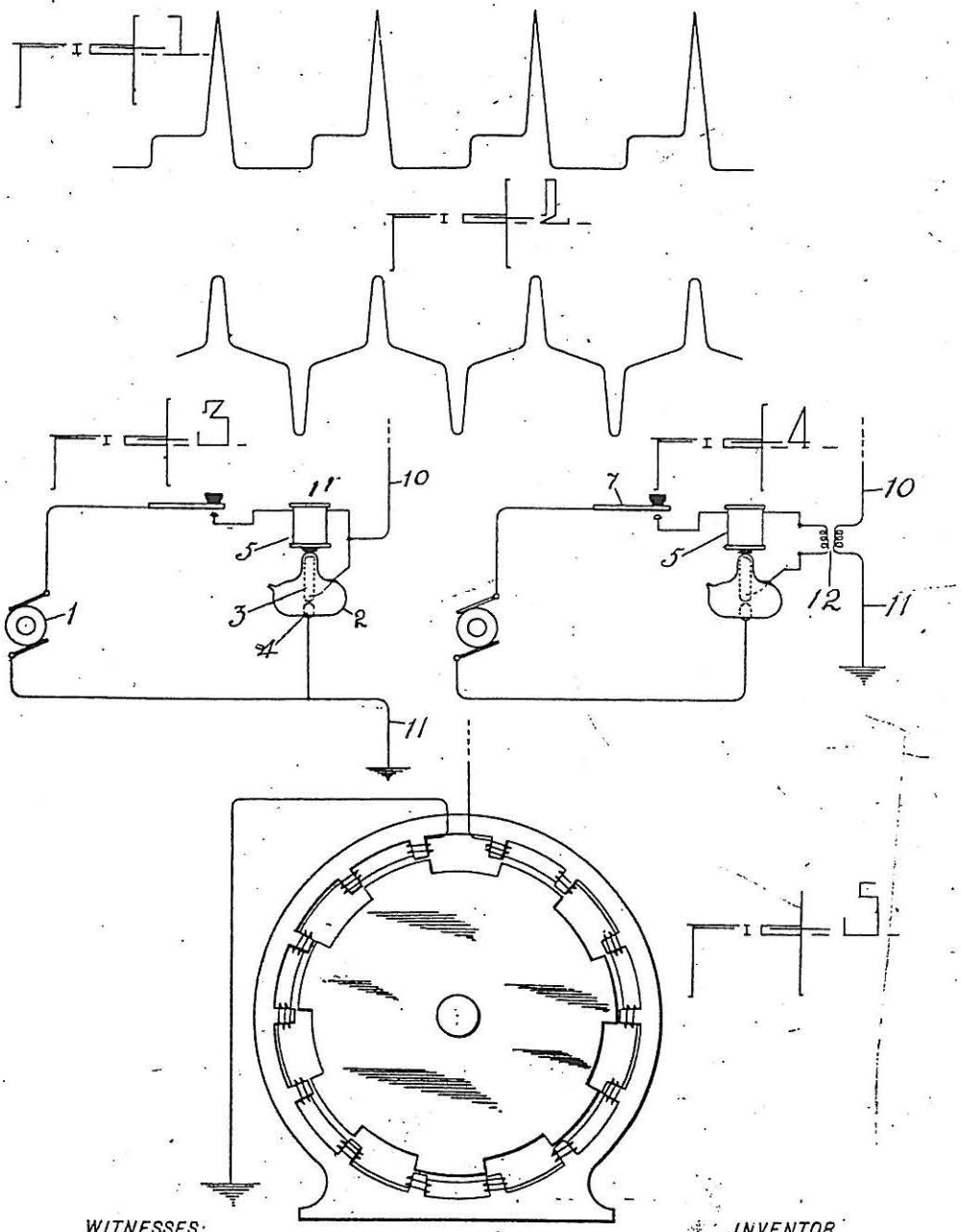
No. 755,305. PATENTED MAR. 22, 1904.

D. McF. MOORE.

PEAKED WAVE WIRELESS TRANSMISSION.

APPLICATION FILED JUNE 14, 1902.

NO MODEL.



WITNESSES:

C. G. Siechmann

E. L. Lawler

INVENTOR

Daniel McFarlan Moore.

BY

Townsend & Hecker

ATTORNEYS

No. 755,305. Patented March 22, 1904.

UNITED STATES PATENT OFFICE.

DANIEL McFARLAN MOORE, OF NEWARK, NEW JERSEY.

PEAKED-WAVE WIRELESS TRANSMISSION.

SPECIFICATION forming part of Letters Patent No. 755,305, dated March 22, 1904.

Application filed June 14, 1902. Serial No. 111,691. (No model.)

To all whom it may concern:

Be it known that I, DANIEL McFARLAN MOORE, a citizen of the United States, and a resident of Newark, in the county of Essex and State of New Jersey, have invented certain new and useful Improvements in Peaked-Wave Wireless Transmission, of which the following is a specification.

My invention relates to a method of setting up waves of radiant electric energy for propagation through space, as in systems of space telegraphy or transmission of power, or for other uses where it is desired to employ similar waves of radiant energy sometimes termed "electromagnetic" or "Hertzian" waves or simply electric waves. It is known that waves of this character can be propagated through space or through the all-pervading ether by changes of electric potential or condition, and it has heretofore been proposed to produce such changes of electric potential or condition by the breaking of electric circuits or the discharge of the same over a space between electrodes, as in the well-known Hertzian oscillator.

Heretofore in developing Hertzian waves or waves of radiant electric energy no attention has been given to the form of the oscillatory waves or pulses of electric condition or potential which primarily excite or produce the ether waves, most experimenters being satisfied with the natural effects resulting from the electric discharge across an air-gap. What I have discovered and what seems to have been completely ignored so far by all other workers in the wireless field is that the shape of the wave is a matter of great importance—that is, the shape of the wave of the circuit, which is the source of ether-radiating waves.

My present invention or discovery is addressed to the manner of primarily exciting or producing the waves of radiant energy; and it consists, substantially, in setting up or originating in any proper way changes of electrical condition or polarization which by reason of their high rate of change will be better suited to produce radiating spheres or lines of wave action that will propagate themselves for greater distances and will act with greater power upon the receiving apparatus. Otherwise stated, the improved method devised by me depends for its efficacy upon the sudden action of the primary exciting cause upon the surrounding ether or medium in which the said waves propagate themselves.

Briefly stated, my invention consists in the improved method of propagating such waves by producing changes of primary exciting electric potential or polarization which if graphically described as a series of waves would show a series of waves of highly-peaked form. Such changes of electrical polarization or condition may be produced by various forms of apparatus, some of which will be herein described. They may be produced, among other ways and with great effectiveness, by interrupting a charged circuit in a high vacuum through simply bringing the two electrodes or contacts of the circuit into and out of contact with one another while included in the vacuum. In this way said contacts may serve practically the double purpose of the ordinary make-and-break device heretofore employed in Hertzian wave telegraphy and the function also of the electrodes of the oscillator or radiator separated by a space over which the discharges primarily produced by the vibrator take place. By "high vacuum" I mean one in which the exhaustion has been carried to the highest practicable degree. The higher the vacuum the better for the purposes of my invention. The apparatus in this simple form suitable for producing the exciting waves or pulses is the same as that described in my prior application filed December 16, 1898, Serial No. 699,423, of which the present application is as to that feature a continuation.

The essence of my invention consists in producing in any manner changes of electric condition or potential for the purpose of developing the free electromagnetic waves radiated through space, by causing changes of electric potential or condition of predetermined form or rate of change which, graphically represented, may be described as a wave or pulse of extremely peaked form, and while the use of a high-vacuum break is the most effective means known to me for setting up such ether vibrations or electromagnetic

waves I do not limit myself to the use of such a device, since the same accentuated change of electric potential or condition in a wire or conductor might be produced by generating the electric potentials directly in a properly-designed dynamo-electric machine of the general character shown in my prior patent, No. 678,191, dated July 9, 1901.

With an induction-coil using an open-air break, due to the conductivity of the air and due to the necessarily longer time constant of secondary coil, it is impossible to produce a wave whose peakedness is at all comparable with that produced by the vacuum break in which the best dielectric known—namely, an extremely high vacuum—inserts itself automatically in the electric circuit, and therefore produces a complete interruption thereof in the minimum length of time.

As is well known, it is desirable that the oscillations or vibrations which excite the electromagnetic vibrations in the ether shall continue as long as possible before they are dampened out, and Maxwell and others have shown that these oscillations would continue for a maximum length of time and with a rapidity approximating that of light if the apparatus from which they emanate were reduced to molecular proportions. It is physically impossible, of course, to produce such an apparatus; but, as I have discovered, great advantage may be secured by primarily exciting the ether vibrations by an impulse or impulses whose character is such as to act with great violence or suddenness upon the ether, and thereby set up electromagnetic waves or vibrations of greater amplitude, and therefore of greater carrying power.

In the accompanying drawings, Figure 1 represents, roughly, one of the forms of the primary exciting waves or impulses which might be generated by a proper device, although such graphic representation cannot of necessity be relied upon as a correct representation of what would take place and is only designed to roughly indicate the direction in which I aim to proceed according to my present invention in the production of the primary exciting cause of the ether vibrations termed "electromagnetic" waves or "electric" waves by Hertz and others. Fig. 2 is a graphic representation of another form of wave or pulse which theoretically might be developed by a dynamo-machine, but which could be given a much more peaked or pointed form by proper attention to the design of the machine. As will be obvious, the form shown in Fig. 2 is a very imperfect realization of the form of primary exciting wave or impulse which should be produced or generated in order to best carry out my invention. Fig. 3 represents diagrammatically an apparatus and circuits adapted for use in practicing my invention. Fig. 4 shows another arrangement of circuits. Fig. 5 illustrates in side elevation the parts of the dynamo constructed to produce the form of pulse or changing potential wave illustrated in Fig. 2.

Referring to Fig. 3, 1 indicates a generator of continuous current preferably, and included in the circuit therewith is the vibratory interrupter 2, composed of a glass receptacle or receiver exhausted to as high a degree as possible and containing the two contacts of an interrupter, (marked 3 and 4.) The lower one, 4, is sealed in the glass body of the receiver, while the upper one, 3, is attached to the vertically-oscillating armature of an electromagnet 5 above the glass extension in which the armature is guided and moved and is included in the circuit passing through the contacts 3 and 4. This device is in its substantial mechanical form the same as the one heretofore employed by me in vacuum-tube lighting and is capable of operation after the manner of an automatic make and break. Its action may be controlled by the key 7 in any obvious way. To improve the effects, antennæ or aerial and ground wires 10 11, such as used in ordinary forms of wireless-transmission plant, may be added. The closure of the key 7 permits the vibrator to act and produce sudden and rapid changes of electric condition which result in the transmission or radiation of the electric waves or electromagnetic vibrations propagated through space to any distant receiver of them, as well understood in the art.

In Fig. 5 I show in skeleton the parts of a dynamo adapted to produce the sudden changes of electric condition which it is desirable to produce in order to best generate the electromagnetic waves. This form is in general shown in my prior patent, No. 678,191, and is merely illustrated herein to indicate the possible variations of my invention, although it is recognized that this particular form of machine and form of generated pulse of electric potential is not the best for the purpose. The terminals of said machine would preferably be connected with the usual aerial and ground wires used in wireless transmission.

In Fig. 4 a wireless-telegraph apparatus is shown wherein an induction-coil 12 is employed. The electric condition developed in the primary according to my present invention has its potential raised by employing in the secondary a larger number of turns, as usual in the art.

The arrangement of apparatus shown in Fig. 3 is especially suited to the practicing of the invention, since through the interruption of the circuit in the vacuum the impulses are very abrupt, while owing to the absence of a secondary the time constant of the circuit in which the oscillations take place is reduced to a minimum.

Other forms of apparatus might be employed in carrying out my invention. The forms shown indicate only some of the de-

P. O. PEDERSEN.

GENERATOR FOR HIGH FREQUENCY CURRENTS.

APPLICATION FILED MAR. 24, 1913.

1,231,528.

Patented June 26, 1917.

Fig. 1.

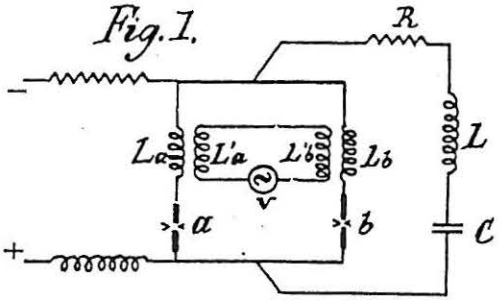


Fig. 2.

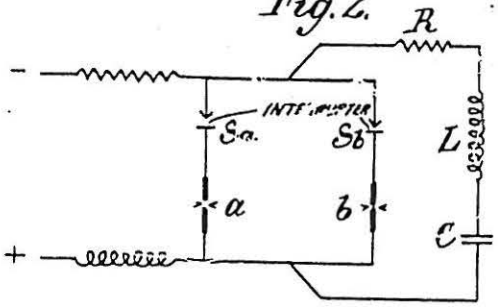


Fig. 3.

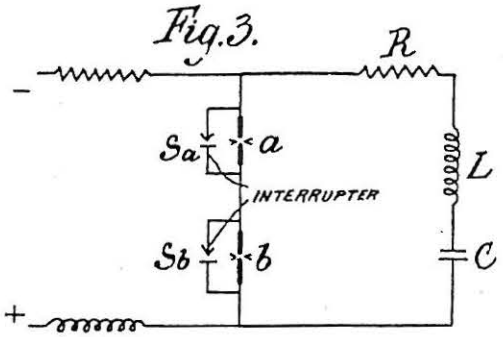
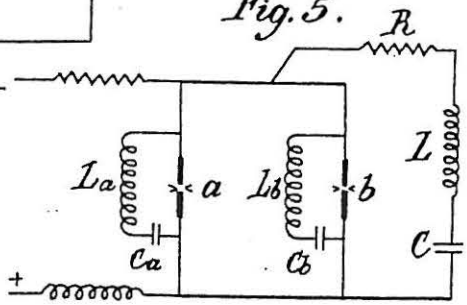


Fig. 5.



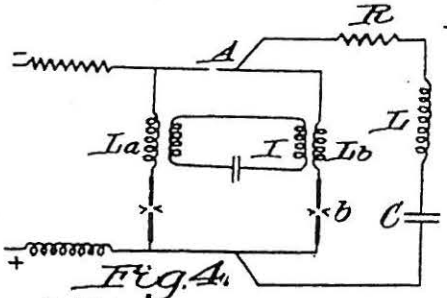


Fig. 4.

Witnesses:

Waldo M. Chapin

Ida M. Patterson

Inventor

Peder Olaf Pedersen

by Ramsauer & Stratton

Attys.

vices that may be employed for generating the exciting electric potential which, considered as a wave or pulse of exciting energy, would be of highly-peaked form.

What I claim as my invention is—

1. The herein-described method of producing waves of radiant energy in space telegraphy or power transmission consisting in impressing upon the ether repeated changes of electrical potential or polarization which, graphically described, would be a series of waves of highly-peaked form.

2. The herein-described method of producing waves of radiant energy for space telegraphy or power transmission, consisting in setting up a series of changes of electric potential in an electric circuit by making and breaking a circuit in a high vacuum as described, thereby subjecting the ether to a series of waves or pulsations of impressed energy or polarization which, graphically represented, would be of highly-peaked form.

8. In the art of wireless transmission of energy, the improvement consisting in generating free electromagnetic waves or vibrations by abruptly breaking a closed circuit in a high vacuum.

Signed at New York, in the county of New York and State of New York, this 13th day of June, A. D. 1902.

DANIEL McFARLAN MOORE.

Witnesses:

J. GALLWITZ,

E. L. LAWLER.

UNITED STATES PATENT OFFICE.

PEDER OLUF PEDERSEN, OF FREDERIKSBERG, DENMARK, ASSIGNOR TO FEDERAL TELEGRAPH COMPANY, A CORPORATION OF CALIFORNIA.

GENERATOR FOR HIGH-FREQUENCY CURRENTS.

1,231,528. Specification of Letters Patent. Patented June 26, 1917.

Application filed March 24, 1913. Serial No. 756,323.

To all whom it may concern:

Be it known that I, PEDER OLUF PEDERSEN, a subject of the King of Denmark, residing at Frederiksberg, near Copenhagen, and Kingdom of Denmark, have invented certain new and useful Improvements in Generators for High-Frequency Currents, of which the following is a full, clear, and exact description.

This invention relates to generators for high frequency currents.

It has been heretofore proposed to produce currents of high frequency by feeding direct current to an oscillatory circuit including a self-induction L, a condenser C, and an arc, the period of the alternating current being equal to $2\pi\sqrt{LC}$ in accordance with Kelvin's formula. However, when this method has been used even where the arc has been arranged in an atmosphere containing hydrogen and the anode of the arc cooled, the maximum frequency which can be obtained is limited, since it is essential that the anode be cooled to prevent the current passing through the circuit from becoming a mere direct current. It is obvious that such cooling of the anode will necessarily limit the frequency which can be obtained.

The object of my invention is to provide a generator with which frequencies, higher than those previously obtained, can be procured, and with this object in view, the invention contemplates the provision of a plurality of arcs which are so arranged that the current impulses pass successively through the arcs, as for example, where three arcs are used only each third current impulse passes through a single arc, and this arc thereafter remains extinguished for two entire periods which gives the arc a sufficiently long time for being cooled. If the shiftings of the arc are promptly timed, this will not affect the period of the alternating currents which passes through the circuit containing the induction L and the condenser C. Instead of changing the arc through which the current passes for each current impulse, it is sufficient if the arc, through which the current passes, is changed after the second, third, etc., current impulse. However in the preferred embodiment of the invention, it is preferable to shift the arc after each period. The period for shifting the arcs need not be in strict accordance with the natural period $2\pi\sqrt{LC}$ of the oscillatory circuit. The period of the alternating current is, of course, determined by the period of the shifting of the arc.

One of the important advantages of the present system is that it provides a sufficiently long time for each arc to cool and deionize, that no special methods for cooling the arc need be utilized. It is also obvious that the discharge completely loses the character of an arc since so long a time elapses between the passage of single current impulses through one of the discharge spaces and the discharges therefore become in effect a series of non-oscillating sparks. Instead of utilizing discharge spaces or arcs, vacuum tubes and the like may also be used, and in cases where the frequency is not too high, simple interrupters may also be used to advantage.

It is also to be understood that it is not necessary to change the entire discharge space through which the current impulses pass, since it will suffice if at least the cathode and a part of the discharge space is changed. In this manner, the same anode may be used for a plurality of discharge spaces.

The invention and its object will be apparent from the embodiments of the invention shown in the drawing, wherein Figures 1 to 5, inclusive, show various modifications of the circuit arrangements which may be used, but it is intended that such modifications and embodiments will be regarded as descriptive and not as limiting the invention.

An example of the use of two arcs or discharge spaces *a* and *b* is shown in Fig. 1. Between the cathodes and the feed conductor are inserted self inductions L*a* and L*b* (which as a rule have the same value), and the circuit of vibration proper is formed by the condenser C, the inductance L and the rheostat R in connection with the inductances L*a* or L*b*. The period is the same, viz. T in both cases. The circuit of oscillation I indicated, the distribution circuit, is coupled to both of the self inductions L*a* and L*b*, and its natural period is 2T. The manner of acting of the system is explained as follows:

If first a current impulse passes through the discharge space *a*, a free oscillation is thereby induced in the circuit I; a period later the oscillation in this circuit will

through the inductance La counteract, that a current impulse again passes the discharge space a, but at same time it will promote the passage of a current impulse through the discharge space b, etc. It is of importance that the damping in the circuit I is as small as possible.

A somewhat different arrangement is shown in Fig. 2. The distributing circuit is here substituted by two coils L'a and L'b coupled to the coils La and Lb respectively; through the two first named coils is passed an alternating current from a generator v; the period of the alternating current is 2T. The manner of acting will easily be understood: each second discharge passes through the discharge space a, each second through the discharge space b. If the period of the alternating currents is 4T, two discharges will pass through the discharge space a, thereafter two discharges through the discharge space b, and so on. Analogical methods can be used at three and more discharge spaces.

Fig. 3 again shows another arrangement. Here Sa and Sb designate interrupters which alternately close and interrupt the connection between the cathodes and the feed conductor. The contact period ought to be in the neighborhood of the period T of the oscillation circuit, or in the neighborhood of nT, where n is an integer. In the latter case first n discharges are passing through the discharge space a, thereafter n discharges through the discharge space b, and so on. For sake of simplicity, in the following n is presumed to be equal to 1. If the duration of the contact, the length of spark, the feed tension and feed current and the values of the resistance R, the inductance L and the capacity C be suitably chosen, it can be obtained that the interrupters Sa and Sb work completely without sparks. If at same time the sparking distances a and b are chosen in such a manner, that the potential between the electrodes during the passage of the current is small, while the ignition tension is relatively high, a very high efficiency is obtained, pretty near all the energy of the direct current being transformed into oscillations. It is a matter of course, that also at this arrangement three or more discharge spaces can be used.

Fig. 4 shows the corresponding arrangement for two discharge spaces in series. The manner of acting will easily be understood.

Fig. 5 shows a somewhat different arrangement. The ignition tensions for the discharge spaces a and b are here so high that ignition will normally not take place, and the discharge spaces a and b are shunted to circuits containing the inductance La, the capacity Ca and the inductance Lb and the capacity Cb, respectively. The value of the products of each inductance and the thereto belonging capacity is chosen in such a manner, that the period for the two circuits, consisting of the discharge space a, the inductance La and the capacity Ca, and the discharge space b, the inductance Lb and the capacity Cb, respectively, is much less than T.

The discharges are incurred by in the inductances La and Lb sudden high tensions being alternately induced which cause sparks to jump through the discharge space a and the discharge space b, respectively, and thereby starts the discharges proper. The starting sparks follow each other with an interval of about nT, where T as usual indicates the natural period of the oscillation circuit. Also at this arrangement the number of discharge spaces is arbitrary.

Having now particularly described and ascertained the nature of my said invention and in what manner the same is to be performed, I declare that what I claim is:—

1. A generator for high frequency currents comprising a single oscillation circuit having a plurality of discharge spaces therein, and means for directing a high frequency current through said oscillation circuit and for successively and periodically directing said current through said spaces at periods which are a simple multiple of the high frequency current passing through the oscillation circuit.

2. A generator for high frequency currents comprising a single oscillating circuit having a plurality of discharge spaces connected in parallel therein, and means for directing a high frequency current through said oscillation circuit and for successively and periodically directing said current through said spaces at periods which are a simple multiple of the high frequency current passing through the oscillation circuit.

In witness whereof, I have subscribed my signature, in the presence of two witnesses.

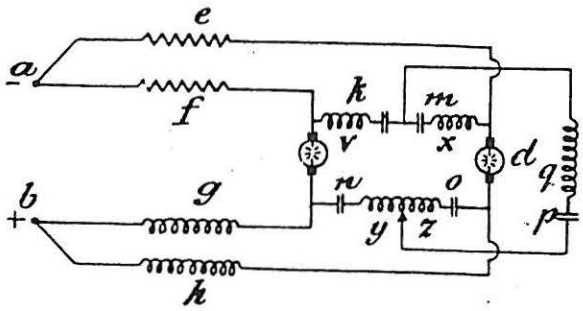
PEDER OLUF PEDERSEN.

Witnesses:
VIGGO BLOM,
VALDEMARCHRISTENA.

Copies of this patent may be obtained for five cents each, by addressing the "Commissioner of Patents, Washington, D. C."

P. O. PEDERSEN & V. POULSEN.
GENERATOR OF HIGH FREQUENCY CURRENTS.
APPLICATION FILED JAN. 6, 1913.

1,214,214. Patented Jan. 30, 1917.



Inventors
Peder Oluf Pedersen
& Valdemar Poulsen
by Rosenbaum & Stockbridge attys

UNITED STATES PATENT OFFICE.

PEDER OLUF PEDERSEN AND VALDEMAR POULSEN, OF FREDERIKSBERG, DENMARK, ASSIGNORS TO FEDERAL TELEGRAPH COMPANY, A CORPORATION OF CALIFORNIA.

GENERATOR OF HIGH-FREQUENCY CURRENTS.

1,214,214. Specification of Letters Patent. Patented Jan. 30, 1917.

Application filed January 6, 1913. Serial No. 740,542.

To all whom it may concern:

Be it known that we, PEDER OLUF PEDERSEN and VALDEMAR POULSEN, subjects of the King of Denmark, residing at Frederiksberg, Denmark, have invented certain new and useful Improvements in Generators of High-Frequency Currents, of which the following is a full, clear, and exact description.

Most generators of the arc or spark type for currents of a high frequency have the peculiarity that under given circumstances, thus for a given wavelength, feeding tension, damping, etc., they are only able to yield up to a certain high frequency effect, and this limit is often lower than desirable. It has been attempted to overcome this difficulty by use of a plurality of generators arranged in series. This is possible in cases in which the high frequency circuit is of considerable resistance, the high frequency currents in this case having only a proportionately low intensity so that no drawbacks of any great importance appear by causing the high frequency currents to pass through all of the generators. But it is quite different when the high frequency circuit must necessarily have a low resistance. This is for instance the case in large stations for radio telegraphy and telephony working with great wave-lengths and therefore having a comparatively small resistance of radiation. In such cases, to obtain a sufficient radiation, it is necessary to work with very strong high frequency currents. If it is here necessary to distribute the high frequency energy over a plurality of generators, a connection in series of these generators will be disadvantageous, as the strong high frequency currents will decrease the efficiency of the generators. A connection in multiple, however, will be highly desirable. The difficulty is found in causing the separate high frequency generators to coöperate in the right manner, whether those generators comprise arcs, spark gaps or the like. If the question is for instance of a Poulsen generator for continuous oscillations, provisions must in the first place be taken to make all of the generators work in the same phase. Even if the frequency was exactly the same, it would be necessary to take special measures in order to secure the correct coincidence of phase. In causing all of the generators to work in parallel in the same circuit of vibrations, another difficulty arises, for instance in the Poulsen generator, which has the peculiarity that the apparent resistance of the generator decreases when the intensity of the current increases. If therefore for some reason or other an unequal distribution of the high frequency current occurs, a tendency will be present to a continuous increasing of the said inequality, so that finally the greater part of the current will fall to one of the generators whereby it becomes less effective, while the other generator eventually becomes currentless, and the aim of the connection in parallel will thus not be attained. Therefore measures must be taken for securing the equal distribution of the high frequency currents over all of the generators.

The present invention will be fully described by reference to the annexed drawing showing schematically an embodiment of the invention, by which a uniform distribution of the high frequency energy over all of the generators can be obtained. In the figure only two generators are shown, but, as a matter of course, three or more can be used if wanted without departing from the spirit of the invention.

a and *b* indicate feeding terminals, *c* and *d* two Poulsen generators, *e* and *f* reducing rheostats, *g* and *h* reaction coils, *k*, *m*, *n*, *o* and *p* condensers, and *q* the self induction of the vibration circuit. This latter consists as it will be seen, of the self induction coil *q*, the condenser *p* and the two parallel circuits comprising: the condenser *k*, the generator *c* and the condenser *n*; and the condenser *m*, the generator *d* and the condenser *o*, respectively. The capacity of the condensers *k*, *n*, *m* and *o* (which will most frequently have the same value) must for two reasons be rather small; firstly they will contribute to forcing the high frequency currents running in the circuit of vibration to distribute themselves more evenly over the generators the smaller their capacity is, and secondly the tendency of high frequency currents arising in the circuit formed by the condenser *k*, the generator *c*, the condensers *n* and *o*, the generator *d* and the condenser *m*, will be the smaller the smaller the capacity of the condensers is. This is a circumstance of very great importance. If the condensers *k*, *n*, *o* and *m* are too large, independent high frequency currents will arise in the above

named circuit, while the circuit of vibration containing the condenser p and the self induction q becomes practically currentless. Finally an eventual difference of phase between the ignitions of the arcs c and d will become smaller the smaller the said condensers are.

According to the invention self induction coils v, x, y and z are inserted in connection with the condensers k, m, n and o. It will especially often be advisable to insert coils like y and z connected and arranged in such a manner that an increasing current in one coil, for instance y, will tend to induce an increasing current in the other coil z, the direction of the current for the two coils being presumed to be positive from the connection point of the coils toward the condensers n and o respectively. Such an arrangement can greatly contribute to lessen the difference of phase between the ignition of the two arcs. Such coils can also be of use in other ways.

Having now described our invention what we claim and desire to secure by Letters Patent of U. S. A. is:

In a system for generating high frequency currents, the combination of a feeding circuit, a plurality of generators connected in parallel in said circuit, a circuit of oscillation in which said generators are also connected in parallel, a plurality of condensers at least one in each branch of the divided portion of the said oscillation circuit and a plurality of self-induction coils, at least one in each branch of the divided portion of the oscillation circuit, the branches being inductively related to each other.

In witness whereof, we have subscribed our signatures, in the presence of two witnesses.

PEDER OLUF PEDERSEN.
VALDEMAR POULSEN.

Witnesses:
CECIL V. SCHOTT,
FIGGO BLAUE.

Copies of this patent may be obtained for five cents each, by addressing the "Commissioner of Patents, Washington, D. C."

F. LOWENSTEIN.

METHOD OF AND APPARATUS FOR GENERATING ELECTRICAL OSCILLATIONS.

APPLICATION FILED NOV. 29, 1918.

1,322,315.

Patented Nov. 18, 1919.

2 SHEETS—SHEET 1.

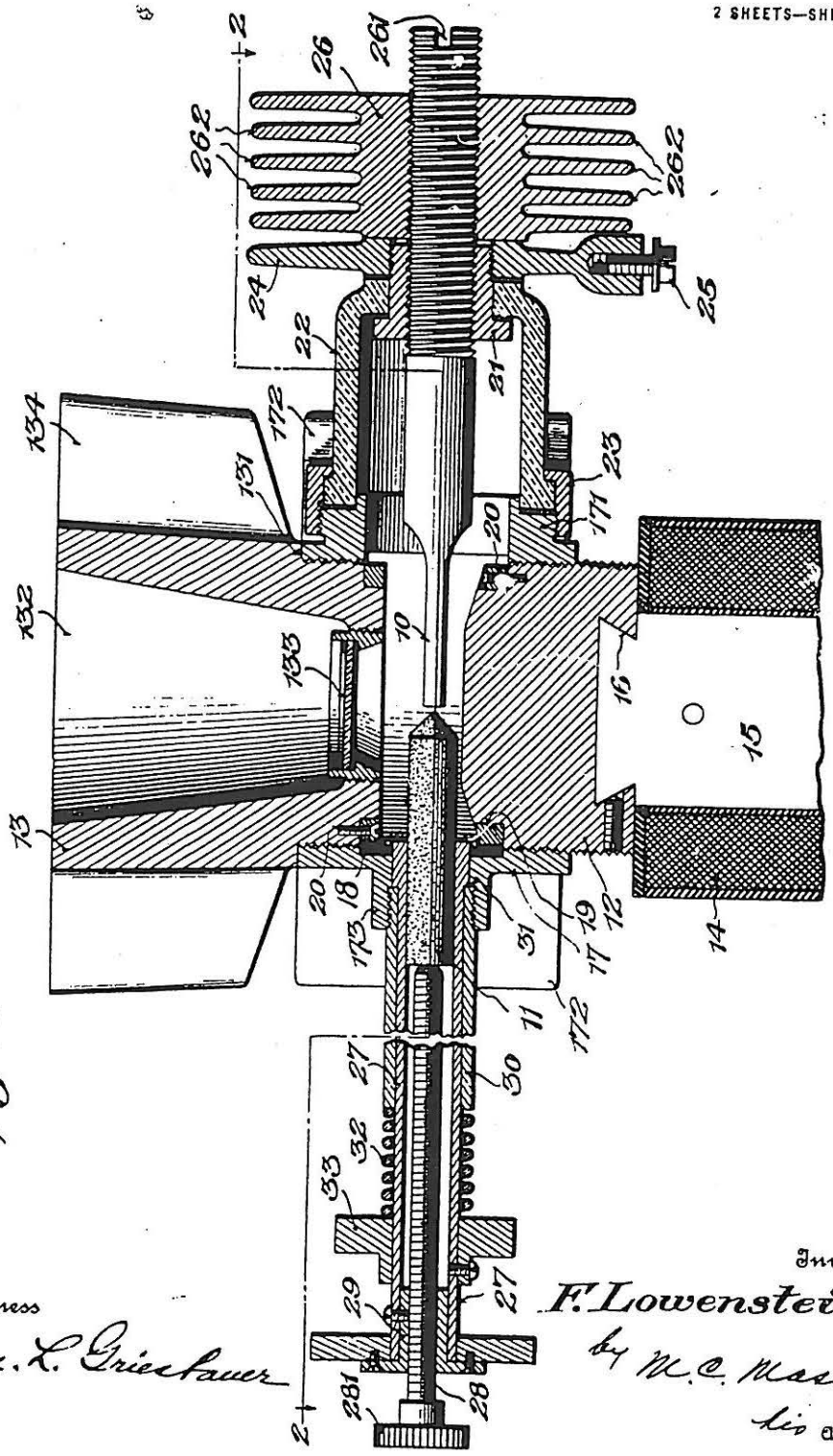


Fig. 1.

Witness

Chas. L. Grieshauer

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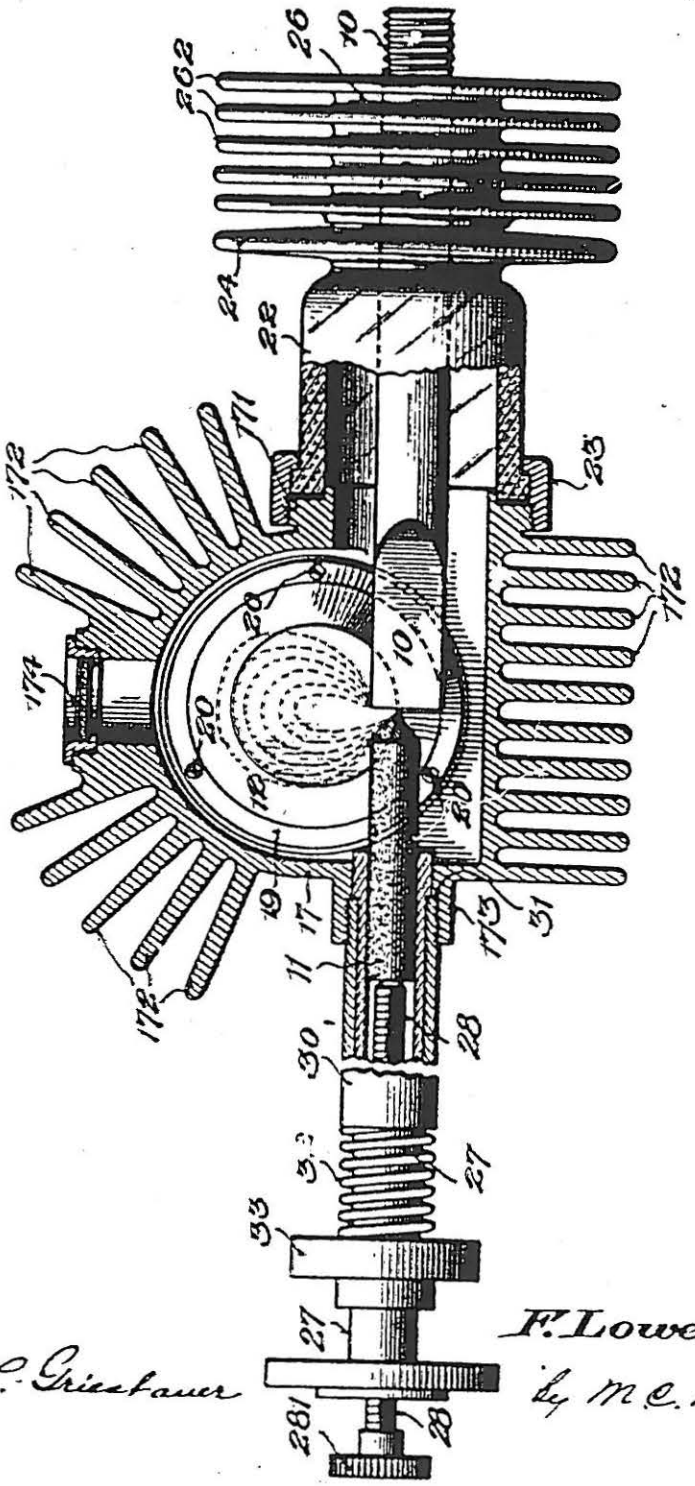


Fig. 2.

Witness
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UNITED STATES PATENT OFFICE.

FRITZ LOWENSTEIN, OF NEW YORK, N. Y.

METHOD OF AND APPARATUS FOR GENERATING ELECTRICAL OSCILLATIONS.

1,322,315. Specification of Letters Patent. Patented Nov. 18, 1919.

Application filed November 29, 1918. Serial No. 264,644.

To all whom it may concern:

Be it known that I, FRITZ LOWENSTEIN, a citizen of the United States, residing at New York, in the county of New York and State of New York, have invented certain new and useful Improvements in Methods of and Apparatus for Generating Electrical Oscillations; and I do hereby declare the following to be a full, clear, and exact description of the invention, such as will enable others skilled in the art to which it appertains to make and use the same.

My invention relates to methods of and apparatus for generating electrical oscillations; and it relates particularly to improvements in the so-called Poulsen arc type of apparatus for producing high frequency or radio oscillations and methods of operating the same.

As is well known, the Poulsen arc apparatus, in a typical form, comprises a source that supplies direct current to a negative carbon electrode and to a water-cooled cylinder of copper constituting the positive electrode. The arc between these electrodes is inclosed in a chamber containing an atmosphere of coal gas, hydrogen, alcohol, vapor, or the like. To increase the power and frequency of the oscillations, the arc is blown or blowed out laterally in some suitable manner, usually by means of a powerful magnetic field acting transversely to the arc.

The arc is ordinarily comparatively unsteady, and when blown or bowed laterally to gain high power the irregularities are increased, causing the arc bow to swing to one or the other side of a plane intermediate the opposed pole pieces of the electromagnet device employed. When the pole pieces are too close together portions thereof are touched from time to time by the arc bow and melted away, and other parts of the apparatus may also be damaged because of the unsteadiness of the arc, which unsteadiness also detrimentally affects the general operating performance of the apparatus.

To avoid damage to the pole faces, they may of course be placed at such distance away from the mid position of the arc that they will not be engaged thereby even when it swings considerably; but this increased air gap between the cores greatly increases the reluctance of the magnetic circuit. To compensate for the weakened field it therefore becomes necessary to increase the ampere-turns of the heavy magnet windings of copper, but this adds considerably to the cost of the apparatus and increases the difficulty of cooling.

It is, therefore, a principal object of my invention to provide a Poulsen arc generating apparatus in which the bowed arc is stabilized and maintained approximately in the desired position intermediate the opposed faces of the magnet poles, so that these faces may be brought comparatively close together, thereby reducing the air gap and the reluctance of the magnetic circuit to an extent unattainable in the type of gap apparatus heretofore known. As a consequence, magnet windings of a very much smaller number of ampere-turns suffice to supply the field necessary to blow the arc.

Another object of the invention is to provide a simple, effective and inexpensive means whereby the arc may be stabilized and maintained in a position where it will operate to best advantage and will not damage the pole faces or other parts of the apparatus.

Another object of the invention is to provide stabilizing means for the arc that may readily be applied to Poulsen arc generating apparatus now in general use, so that no substantial alterations in existing apparatus of that type will be necessary.

In carrying my invention into practice I employ means whereby an electrical force is applied in such manner as to tend to keep the blown arc away from the opposed ends of the pole pieces of the blowing magnet. Such electrical force may of course be set up and applied in various ways. An arrangement which I have found in practice to be especially simple and effective consists in placing copper rings on opposite sides of the arc parallel to the desired intermediate plane positions of the arc and in a position where they will be affected by changes in the magnetic field between the magnet pole pieces. The parallel copper rings are preferably mounted on the adjacent or opposing faces of said pole pieces, being most conveniently secured in annular recesses in the faces thereof. The operation of the arc causes changes in the magnetic flux, thereby inducing eddy currents in the rings, and these currents exert forces which operate to steady the blown arc and keep it away from the faces of the poles.

The foregoing and other objects and the

novel features of the invention will be still more fully apparent from the following description taken in connection with the drawing, in which—

Figure 1 is a vertical section through apparatus embodying the invention in particularly desirable form; and

Fig. 2 is a plan, partly in section on the line 2—2 of Fig. 1.

In the specific embodiment of the invention here illustrated, the arc is blown or bowed by means of a magnetic field, which in this instance is set up through the agency of an electromagnet.

Referring to the drawings, 10 is the positive electrode, which is usually of copper and which may be internally water cooled in any appropriate manner; and 11 is the negative electrode, usually of carbon. At 12 is one end or pole of a bar electromagnet; while above and spaced away from this pole piece is another pole piece 13 which is circular and which serves mainly to concentrate the field lines in the intervening space. Both the pole pieces are of iron, and the upper one may have radial flanges or fins 134 which serve not only in directing the course of the lines of force, but also as heat-dissipating means. The electromagnet comprises energizing copper windings 14 on a laminated iron core 15, which latter may be secured to the pole piece 12 in any suitable manner, in this instance by a dove-tail connection 16. In the particular construction here shown, the arc electrodes are in axial alinement and are disposed eccentrically with respect to the circular faces of the pole pieces. This particular arrangement, while most desirable in practice, is not essential to the broad invention. The arc formed between the electrodes is inclosed in a chamber, the upper and lower walls of which are formed by the pole faces; while the lateral walls are formed by a casing or shell 17 of bronze or other nonmagnetic metal, most desirably provided with heat-dissipating fins 172, the pole pieces being most conveniently arranged to screw into this shell from above and below, as shown. In the construction illustrated, the upper pole piece is screwed down until the shoulder 131 engages the upper edge of the casing; while the position of the lower pole piece with respect to the arc can be adjusted as desired. Suitable means (not shown) are provided for introducing hydrogen, alcohol vapor, or the like, into the arc chamber.

Under the influence of the field provided by the electromagnet, the arc is blown out laterally between the pole faces as indicated in dotted lines in Fig. 2. Means are provided for steadying the arc and preventing its being diverted to one or the other of the pole faces. In the specific construction illustrated, which is a particularly desirable embodiment of the invention, such means comprise continuous or short-circuited rings 18 and 19, of copper or other highly conductive metal, encircling the upper and lower pole faces, respectively. These rings may be secured to the pole faces in any suitable manner. As here shown, each is seated in an annular peripheral recess formed on the pole face and is held in place by screws 20.

Any suitable method of holding the arc electrodes in position may be adopted, but the present arrangement offers practical advantages. As here shown, the copper electrode is supported for longitudinal adjustment in an internally threaded conductive bushing 21, which is mounted in a heavy insulating support 22, of porcelain or the like, secured to a hollow boss 171 on the casing by coupling member 23. A flange 24 screws into place on the end of the bushing 21, and locks the bushing firmly to the porcelain insulator. A binding post 25 carried by the locking flange, provides means for connecting the copper electrode to the positive side of a direct current generator or other suitable source of current, the circuit being completed through the negative electrode 11 to ground by way of the metallic parts in contact therewith.

The position of electrode 10 is capable of longitudinal adjustment by virtue of its screw-thread mounting in the bushing 21; but the electrode is locked against accidental turning by the nut 26, which is normally screwed firmly against flange member 24. By backing the nut away slightly, the electrode can be readily turned in one direction or the other with the aid of a tool inserted in the kerf 261, until the desired adjustment is effected, whereupon tightening up the nut 26 again will secure the electrode in its adjusted position. Said nut may also aid in dissipating heat from the electrode, and to this end may be provided with fins 262.

The carbon electrode 11 is frictionally held in a metal sleeve 27, and may be fed longitudinally therein toward the other electrode by means of an abutting feed screw 28, which has a threaded connection at 29 to the sleeve 27. The sleeve 27 is longitudinally slidable in a metal tubular support 30, which screws into a hollow boss 173 on the casing or shell 17. A stop shoulder 31 on the sleeve 27 is normally pressed against the inner end of member 30 by a compression spring 32, which is confined between the outer end of member 30 and a collar 33, said collar being adjustably fixed on sleeve 27. The purpose of this arrangement is to enable the arc to be readily started. By pushing inwardly on the insulation knob 281 of the feed screw against the spring, the sleeve 27, and with it the carbon electrode, are moved to the right, the carbon thus being brought into

contact with the copper electrode to close the arc circuit. Upon release of the knob 281, the spring operates to separate the electrodes and draw the arc.

In the particular construction here illustrated, the upper pole piece 13 is hollowed out at 132 and provided with a glass window 133 through which the condition of the arc may be observed. Another window 174 may be provided in the casing 17 for the same purpose. It is to be understood that these features, while desirable in many instances are not essential to the broad invention.

The operation of the arc is apparent from the foregoing description. The arc having been formed and blown or bowed laterally, it acts to modify the transverse blowing field created by the electromagnet, and to cause the lines of force to cut the highly conductive rings 18 and 19, thereby setting up eddy currents in said rings. These eddy currents, in turn, exert electrical forces tending to repel the blown arc from both pole faces and to maintain the same relatively steady in a position intermediate said pole faces and spaced away from both. As a result the arc is relatively steady and the destructive action on the pole faces, usual in constructions heretofore known, is practically eliminated, and the general operation of the arc is improved. As a consequence of the greater stability of the arc, it becomes possible to materially cut down the distance between said pole faces, thus diminishing the magnetic reluctance, and consequently reducing the number of ampere-turns necessary to energize the electromagnet. As the copper windings constitute the largest factor of cost in the manufacture of the arc apparatus, a saving in this direction means a substantial reduction in manufacturing cost. Furthermore, the size of the arc chamber is reduced considerably, with the result that the explosion which always accompanies an initial starting of the arc, due to the presence of a combustible mixture in the arc chamber, is materially lessened.

What I claim is:

1. In electrical oscillation generating apparatus, the combination with means for producing an arc, of means for producing a bow in the arc, and means for maintaining the plane of such bowed arc substantially constant.

2. In electrical oscillation generating apparatus, the combination with means including electrodes for producing an arc, of means arranged to bow the arc, and electrical means for steadying the bowed arc.

3. In electrical oscillation generating apparatus, the combination with means for producing an arc, of electromagnetic means arranged to blow the arc, said electromagnetic means comprising a magnetizable pole piece and means tending to repel said arc from said pole piece.

4. In electrical oscillation generating apparatus, the combination with means, including electrodes for producing an arc, of electromagnetic means arranged to blow the arc, and a highly conductive member arranged adjacent said electrodes and adapted to have eddy currents set up in it by the action of said arc.

5. In electrical oscillation generating apparatus, the combination with means, including coaxial electrodes, for producing an arc, of electromagnetic means arranged to blow the arc, and highly conductive members arranged on opposite sides of said electrodes and adjacent thereto, said members being adapted to have eddy currents set up in them by the action of the arc.

6. In electrical oscillation generating apparatus, the combination with means for producing an arc, of an electromagnet arranged to blow said arc, and means whereby the effect produced on the field by the current in said blown arc is utilized to stabilize the same.

7. In electrical oscillation generating apparatus, the combination with means, including electrodes, for producing an arc, of electromagnetic means arranged to blow the arc, said electromagnetic means comprising a magnetizable pole piece, and a short-circuited ring associated with said pole piece and adapted to have eddy currents set up in it by the action of the blown arc.

8. In electrical oscillation generating apparatus, the combination with means, including electrodes, for producing an arc, of electromagnetic means arranged to blow the arc, said electromagnetic means comprising a pair of pole pieces between which said electrodes are disposed, and means whereby the blown arc is repelled from both said pole pieces.

9. In electrical oscillation generating apparatus, the combination with means, including electrodes, for producing an arc, of electromagnetic means arranged to blow the arc, said electromagnetic means comprising a pair of pole pieces between which said electrodes are disposed, and means whereby electrical forces are set up which act transversely of the plane of the blown arc and tend to maintain the arc away from both said pole pieces.

10. In electrical oscillation generating apparatus, the combination with means, including electrodes, for producing an arc, of electromagnetic means arranged to blow the arc, said electromagnetic means comprising a pair of pole pieces between which said electrodes are disposed, and members associated with said pole pieces in such manner that the arc also produces currents in said members acting transversely of the plane

of the blown arc and tending to maintain the arc away from both said pole pieces.

11. In electrical oscillation generating apparatus, the combination with means, including electrodes, for producing an arc, of electromagnetic means arranged to blow the arc, said electromagnetic means comprising a pair of pole pieces between which said electrodes are disposed, parallel short-circuited rings mounted on the ends of said pole pieces adjacent the arc, whereby the action of the blown arc generates currents in said rings acting transversely of the arc and tending to stabilize the same and maintain it away from the said pole pieces.

12. The method of regulating an oscillation-generating arc of the Poulsen type which comprises blowing the arc, and applying an electrical force transversely of the blown arc to steady the same.

13. The method of regulating an oscillation-generating arc of the Poulsen type which comprises blowing the arc, and subjecting the blown arc to the steadying action of eddy currents set up by the arc oscillations.

14. The method of generating electrical oscillations which comprises maintaining an arc in a magnetic field arranged to blow the arc, and utilizing the action of the current in said arc on the field to steady the arc.

15. The method of generating electrical oscillations which comprises maintaining an arc in a magnetic field arranged to blow the arc, and utilizing the action of the current in said arc on the field to create eddy currents in planes on opposite sides of said arc and adjacent thereto, said eddy currents acting to steady said arc.

In testimony whereof I hereunto affix my signature.

FRITZ LOWENSTEIN.

F. LOWENSTEIN.

SPARK GAP DEVICE.

APPLICATION FILED AUG. 25, 1914.

1,305,816.

Patented June 3, 1919.

2 SHEETS—SHEET 1.

Fig 1.

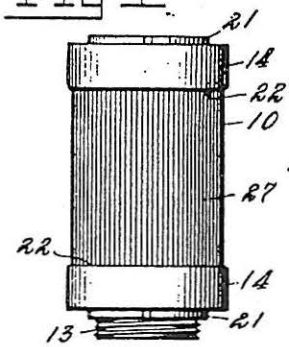


Fig 3

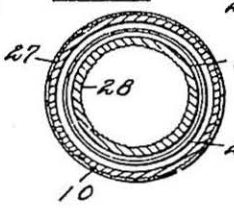


Fig 2

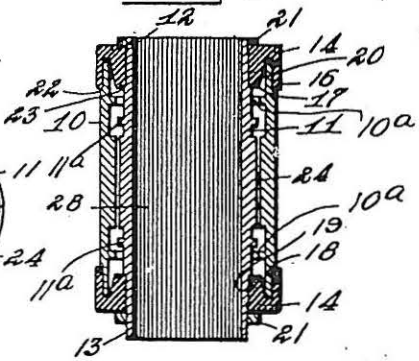


Fig 6

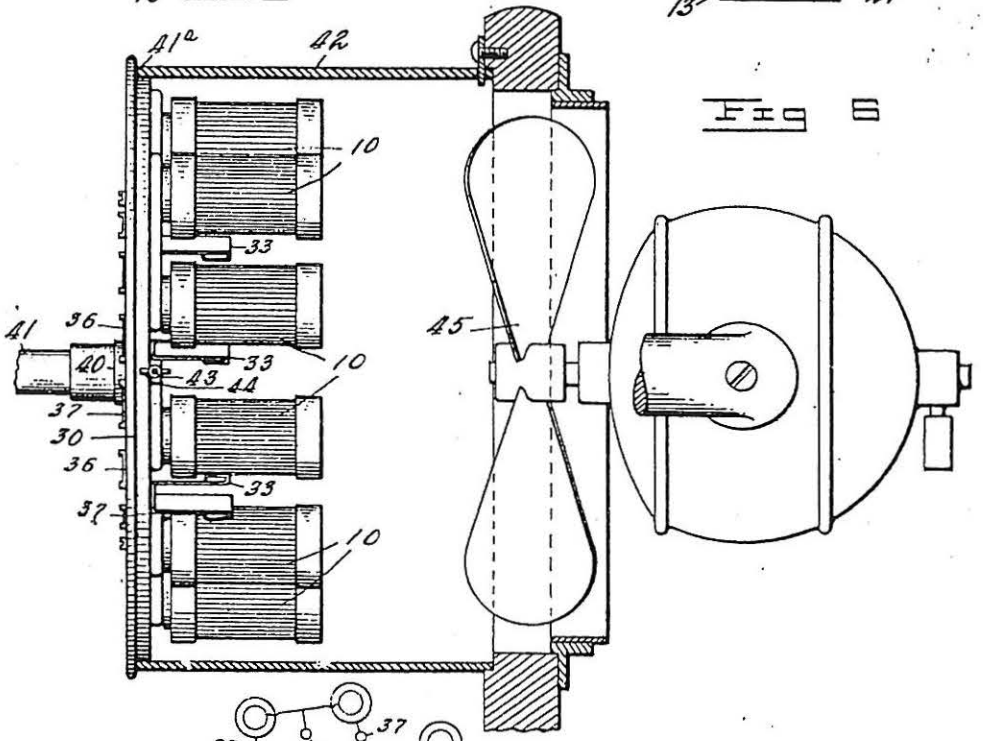
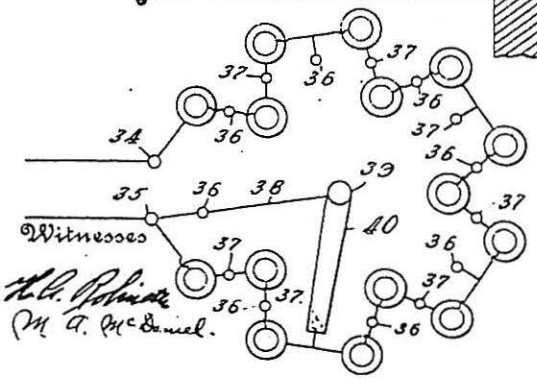


Fig 7



Witnesses

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SPARK GAP DEVICE.

APPLICATION FILED AUG. 25, 1914.

1,305,816.

Patented June 3, 1919.

2 SHEETS—SHEET 2.

Fig 4

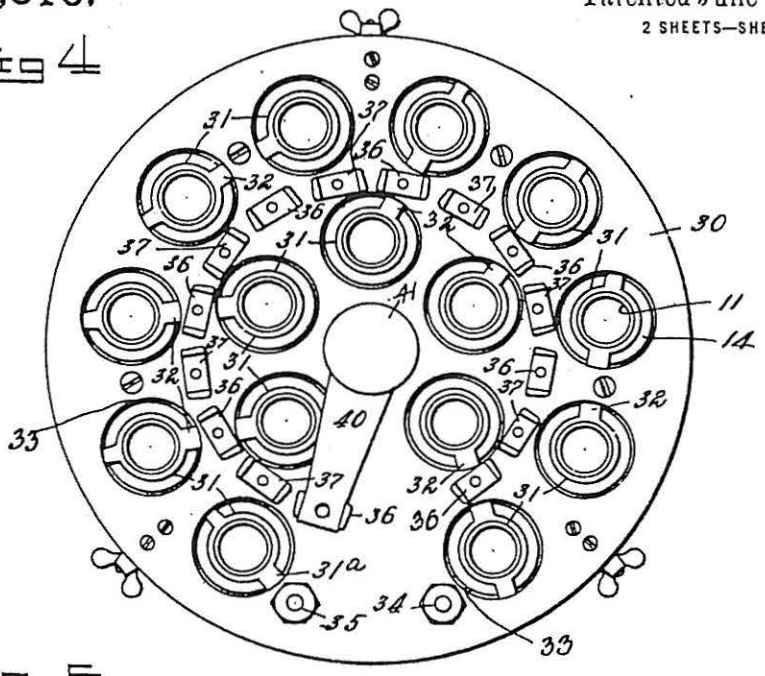
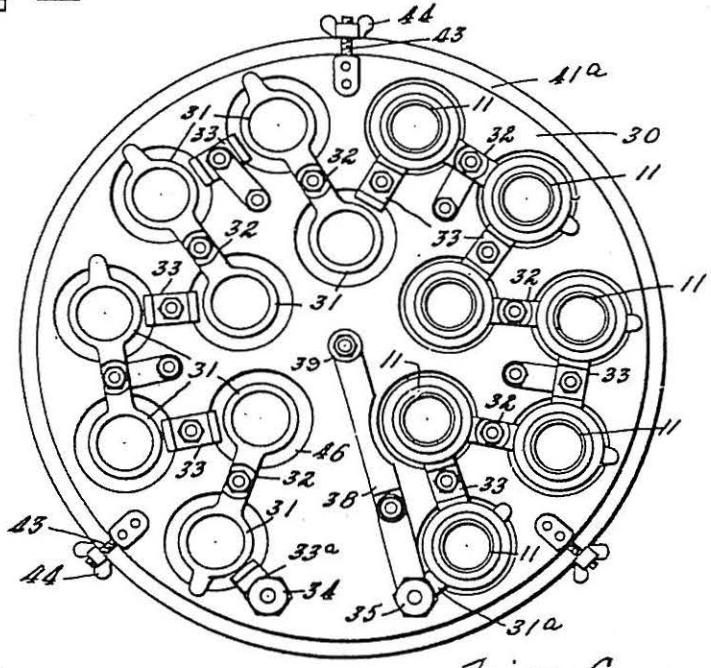


Fig 5



Witnesses

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M. A. McDaniel

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UNITED STATES PATENT OFFICE.

FRITZ LOWENSTEIN, OF BROOKLYN, NEW YORK.

SPARK GAP DEVICE.

1,305,816. Specification of Letters Patent. Patented June 3, 1919.

Application filed August 25, 1914. Serial No. 858,499.

To all whom it may concern:

Be it known that I, FRITZ LOWENSTEIN, a citizen of the United States, residing at Brooklyn, in the county of Kings and State of New York, have invented certain new and useful Improvements in Spark-Gap Devices, of which the following is a specification.

This invention relates to spark gaps for use especially in wireless or radio signaling installations; and it has to do more particularly with spark gaps of the general type known as quenched gaps.

The principal objects of the invention are: to provide spark gap apparatus of relatively simple construction, the component parts or essential elements of which shall be individually removable and replaceable when necessity arises without disassembling the spark gap structure as a whole; to provide for easy and rapid adjustment of the spark length to suit different operating conditions; to provide a spark gap element or unit of novel form and particularly advantageous characteristics; and to insure efficient quenching and uniform length of the spark gap. Other objects of the invention will appear as the description proceeds.

In order to illustrate clearly the principles of the invention, the application thereof specifically to spark gaps for wireless telegraphy will be more particularly referred to herein, this being at present the most important use for which the invention is adapted.

In the usual types of wireless telegraph systems now in practical use, the apparatus at the sending station comprises an antenna included in what is known as the open or radiating circuit, to which circuit energy is supplied by a closed or oscillating circuit suitably supplied with alternating current from any convenient source. This oscillating circuit comprises inductance, a condenser, and a spark gap across which sparks are made to pass when it is desired to radiate signals from the antenna. The character and construction of the parts constituting this spark gap is a matter of great importance since the nature of the sparks produced, and consequently the operation of the whole sending system, are profoundly influenced thereby. The present invention is directed principally to improvements in spark gaps adapted for use in this way in wireless telegraphy.

One of the principal requirements to be met in a spark gap device is the necessity for cooling the electrodes of the gap in order that they may be insulated from each other with the utmost rapidity after each spark discharge passing between them. Various methods of cooling the gap electrodes have been proposed heretofore, but they have not been altogether satisfactory and have generally involved more or less complicated construction of the electrodes or auxiliary parts.

In a practical form of the present invention the sparks pass between a pair or pairs of parallel cylindrical surfaces of ample area suitably insulated from each other and best formed in such manner as to favor very rapid dissipation of heat from the surfaces in question. The term cylindrical as herein employed is to be understood in a broad sense as including prismatic as well as strictly cylindrical surfaces, though right cylindrical surfaces proper are much the best in practice. Furthermore the invention in its broadest aspects contemplates the use of other types of surfaces such as conical or spherical surfaces which may be so arranged and spaced apart with substantial uniformity as to provide an air gap substantially annular in cross section: the term annular to be understood moreover as not restricted to a true circular annulus, but as applying broadly to areas included between two curves or polygons more or less concentrically arranged. A spark gap of this character is herein termed broadly a tubular spark gap.

For the sake of a concrete example and in order to explain clearly the principles of the invention thus broadly defined, an especially desirable practical embodiment thereof is illustrated in the drawings and is hereinafter described in detail, such illustrative embodiment comprising a pair of hollow right cylindrical shells or tubes arranged coaxially one within the other, and suitably spaced apart and insulated from each other to provide between adjacent surfaces an annular gap or space of uniform width.

It is also desirable in practice to divide the total requisite length of the spark gap

in the oscillating circuit into a plurality of relatively small component or elementary gaps arranged in series whose combined or aggregated lengths equal operatively the length of spark gap necessary. Among the advantages of this general type of construction are the quenching of the oscillations in the closed circuit and more or less complete elimination of noise from the spark. Various forms of quenched gap have been proposed heretofore; but, among other defects, they have the disadvantage that if any of the component gap elements have to be removed for repair or replacement, this cannot be effected without disturbing other gap elements in the series, and practically taking apart and reassembling the complete gap structure. Such a procedure involves loss of considerable time which may cause a fatal delay under some circumstances; and it also involves expert work which may not be conveniently available.

This and other defects inherent in quenched gaps as heretofore proposed are obviated in my improved construction herein described in which the component gap elements, which are broadly of the tubular type above disclosed, are so assembled and mounted that any spark gap element or unit is individually removable and replaceable practically in an instant without disturbing or removing any other component unit of the complete gap structure, and without the exercise of any special skill on the part of an attendant operator. Furthermore the arrangement is such that the number of component spark gap elements or units in the series may be readily varied at will to adjust the total spark length in response to working requirements.

These and other important features and advantages of the present improved spark gap apparatus will be more fully pointed out in the following detailed description and in the claims, particular reference being had to the accompanying drawings which are to be understood as illustrating, for the sake of an example, certain particularly advantageous forms of apparatus in which the principles of the invention may be embodied. In these drawings

Figure 1 is a view in side elevation of a tubular spark gap device constructed in accordance with the invention;

Figs. 2 and 3 are longitudinal and transverse sections, respectively, of the same;

Fig. 4 is a view of one face of a base or holder on which a plurality of spark gaps are mounted;

Fig. 5 is a view of the opposite or rear face of the switch board, some of the gap units having been removed to show the connections more clearly;

Fig. 6 shows the switch board assembled with a cooling drum and fan;

Fig. 7 is a diagram of the connections on the switch board.

Referring to Figs. 1, 2 and 3 of the drawings, the spark gap device as here shown comprises an outer cylindrical shell 10, within which is co-axially disposed an inner shell 11 which in this instance projects unequal distances beyond the ends of the outer shell, these projecting portions being threaded as at 12 and 13. These shells or electrodes are made of conducting material such as copper and are spaced apart and insulated from each other by insulating rings 14, each of which is slotted or channeled along one side to accommodate an end of the outer shell or sleeve. Each insulating ring is thus divided into two connected parts, 16 and 17, whose parallel inner faces 18 and 19 engage the convex surfaces of the outer and inner shells, respectively. The parts 17 of the insulating rings extend between and space apart the shells to form the spark gap; and the outer faces 20 of these parts may be slightly sloped or beveled as shown. The insulating rings may be locked in place as by means of threaded collars 21 which are adapted to be turned down on threaded portions 12 and 13 of the inner shell into locking abutment with said rings. When the rings are in proper position they abut against shoulders 22 and 23 on the outer and inner shells respectively. This form of joint between the insulating rings and the shells or electrodes insures that the spark gap space is sealed substantially air tight, which is desirable. The seal persists even when the electrodes become heated and expand; for in the event of such expansion the electrodes press against the ring surfaces 18 and 19, which are similarly located as regards resistance offered to the radial thrust of the shell expansion, and the tightness of the joint is therefore maintained.

The method of construction just described unites the pair of electrode shells into a compact and substantially unitary spark gap element, adapted to be inserted as a distinct unit into series with other similar units, or to be removed as a unit from such series. In the present example, the longer threaded extension 13 of the inner electrode serves conveniently in connecting the spark gap element in such a series, as will be more fully hereinafter described. Obviously various other expedients could be adopted for this purpose.

Another advantage secured by this construction is that the clamping pressure of terminal rings 14 and collars 21 is exerted in a direction parallel to the gap surfaces, so that the width of the gap is independent of the clamping pressure. Where gap electrodes are held by clamping means exerting pressure transversely of the gap surfaces, as in constructions heretofore known,

the width of the gap, and hence the performance of the sending system, varies with the degree of clamping pressure. This disadvantage is evidently avoided in the present device.

As shown, the central or intermediate portions 24 of the electrodes are formed in such a way that the annular spark gap space is narrower at this locality than toward the ends; and it is at this locality that the sparks actually pass between the electrodes. Annular circumferential ribs 10ª and 11ª formed on the electrodes 10 and 11, respectively, project into the wider portions of the gap space and are in staggered or non-registering arrangement. These ribs act as baffles to prevent particles of metal from being "spattered" or otherwise transferred from the spark to the insulating surfaces at the ends of the gap, thus preventing deposit of metal on said surfaces and consequent destruction of their insulating properties.

The outer or convex surface 27 of the outer electrode shell and the inner or concave surface 28 of the inner shell are longitudinally grooved or fluted to provide a large radiation surface for rapidly dissipating the heat from the spark. In practice, when the spark gap is in operation, both these surfaces are bathed with air which is impelled by a fan or other means parallel to the grooves and in close proximity thereto.

Since these heat-dissipating surfaces are parallel to and coextensive with the elementary spark gap included between them, and are separated from said gap only by the thickness of the copper electrode walls, the heat developed in the gap has only to pass directly inwardly and outwardly from the gap through said walls in the direction of their thickness, and is thus dissipated with maximum efficiency. In multiple gap constructions heretofore commonly used, in which the gap was made up of parallel flat plates spaced apart to form a series of gap elements, the heat from each elementary gap had to be transmitted parallel to the gap to the outer peripheries of the plates, being thus conducted a much greater distance than in the present tubular construction.

Various methods may be adopted for connecting up a number of these tubular gaps in series to obtain any desired total spark length, but that illustrated in Figs. 4, 5 and 6 has proved particularly desirable in practice. A circular disk 30 of insulating material serves as a mounting base and switch board and supports a plurality of metal rings or sockets 31 which are threaded to receive the threaded ends 13 of the inner electrodes of the tubular spark gaps which may thus be independently attached to the board. In the present example, fifteen such sockets are provided, but obviously any other convenient or necessary number may be used. With the exception of the terminal socket 31ª, the sockets are electrically connected in pairs, in this instance by means of metal bars 32 formed integral with and supporting the sockets of each pair, said bars being bolted or otherwise suitably secured to the rear side of the board. Double spring contacts 33 are mounted on the board so as to press against and electrically connect in pairs the outer shells or electrodes of spark gap units screwed into adjacent but electrically unconnected socket rings. Spring contact 33ª connects the outer shell of the spark gap element at one end of the series to terminal binding post 34; while socket ring 31ª and its bar connect the inner shell of the gap element at the other end of the series to terminal binding post 35. The arrangement is such that the spark gap elements are connected in series between the terminals 34 and 35, at which terminals the necessary connections may be made to include the complete spark gap in the oscillating circuit of a sending apparatus.

On the opposite or front side of the board, contact points 36 are electrically connected to and represent intermediate points in the respective connections 32 between the inner shells of each connected pair; while contact points 37 similarly represent intermediate points in the outer shell pair connections 33. Conductor 38 connects binding post 35 with a central post 39 and a rotatable switch or contact arm 40 carried thereby and operable by means of an insulated handle 41. This switch is arranged to move over and contact with the circular series of switch points 36, 37; and in the showing of Fig. 4, when the switch is moved clockwise (counter-clockwise in Fig. 7), it short-circuits one by one an increasing number of gap elements, thus shortening the total effective spark length. When the switch is turned in the opposite direction, more gap elements are brought into circuit and the effective spark length is thereby increased. The switch points may conveniently be numbered *seriatim* so that the number of gap elements in series at any time is indicated by the number of the point with which the switch is in contact at that time.

If for any reason one of the spark gaps is not working properly, it can be quickly unscrewed from its socket and replaced by another spark gap with hardly a moment's delay, the necessary connections of its electrodes to the rest of the series being automatically made in the act of inserting it into its socket.

The edge of the switchboard may be shouldered as at 41ª for engagement with the end of a drum 42 of insulating material, attachment being aided by threaded

studs 43 and wing nuts 44. A motor driven fan 45 is arranged to draw air into the drum through openings 46 in the board adjacent the socket rings or holders. These openings are best of somewhat greater diameter than the tubular spark gaps and are substantially concentric with the ends thereof. Air drawn by the fan therefore flows through an annular passage bounded by the edges of each opening 46 and the outer edges of the adjacent spark gap end, traveling as a fairly well defined enveloping mantle longitudinally of the spark gap in close contact with the outer fluted surface thereof. At the same time, air is passing through the hollow inner electrode along its fluted concave surface. As a result of this arrangement a highly effective cooling action is secured.

What I claim is:

1. Spark gap apparatus comprising an insulating base, electrically connected tubular spark gaps terminally attached to said base, openings extending through said base adjacent the ends of said spark gaps, and means for causing flow of air through said openings and longitudinally of said spark gaps.

2. Spark gap apparatus comprising an insulating disk, holders mounted thereon and electrically connected in pairs, tubular spark gaps each having an outer and an inner electrode shell of which the latter is removably secured to a holder, and means electrically connecting in pairs the outer shells of those spark gaps whose inner shells are not connected in pairs by the holder connections, the arrangement being such that the spark gaps are connected in series.

3. Quenched spark gap apparatus comprising a plurality of gap units electrically connected in series and so mounted that each of the units is individually removable independently of the others, in combination with switch means operable to include a variable number of said units effectively in circuit.

4. Quenched spark gap apparatus comprising a plurality of coöperating spark electrodes electrically connected to provide a suitable number of elementary gaps in series, said electrodes being arranged in a plurality of separate gap structures, each individually removable from the complete gap apparatus without disturbing the others, in combination with switch means operable to include a variable number of said separate gap structures in circuit.

5. Quenched spark gap apparatus comprising the combination with supporting means, of a plurality of spark gap elements supported thereby, and electrically connected in series, a plurality of switch contacts connected to different points in the series of gap elements, switch means movable to engage said contacts, and means for connecting said switch means and a point in said series of gap elements to a power circuit, whereby the effective number of gap elements in circuit may be varied.

6. Quenched spark gap apparatus comprising the combination, with a supporting base provided with a plurality of apertures, of a plurality of tubular spark gap members each supported in longitudinal alinement with one of said apertures, said members being electrically connected in series, switch contacts connected to different points in said series and mounted in a circular arc on said base, a switch arm pivotally secured to said base and movable to engage said contacts, and a fan arranged to move air longitudinally of said gap members.

7. A spark gap holder comprising, in combination, an insulating base, a plurality of gap unit supports mounted thereon and arranged to connect in series removable spark gap units, and switch means adapted for connection in an oscillation circuit and operable to make electrical connection with different supports of said plurality, said switch means being mounted on said base.

8. A spark gap holder comprising, in combination, an insulating base, a plurality of gap unit supports mounted thereon and arranged to connect in series removable spark gap units, contacts connected to said supports, and switch means adapted for connection in an oscillation circuit and arranged to coöperate with said contacts.

9. A spark gap device comprising coöperating electrode members spaced apart to provide a suitable gap and separated by insulating means, said device embodying provision for shielding said insulating means from direct exposure to the gap.

10. A tubular spark gap device comprising inner and outer conducting shells in substantially coaxial arrangement, and insulating members spacing said shells apart to provide a spark gap, said device embodying provision for shielding said insulating members from direct exposure to the gap.

11. A tubular spark gap device comprising inner and outer conducting shells in substantially coaxial arrangement, insulating rings spacing said shells apart to provide a spark gap, baffle means shielding said rings from direct exposure to the gap, and means for securing said insulating rings in position and coöperating therewith to secure said shells together.

12. A tubular spark gap device comprising inner and outer cylindrical conducting shells in substantially coaxial arrangement, insulating rings arranged near the ends of said shells and spacing them apart to form a tubular spark gap of greater width adjacent the ends than in an intermediate locality, and ribs projecting from said shells into the wider portions of the spark gap.

13. Spark gap apparatus comprising a supporting plate of insulating material, a casing closed at one end by said plate, a plurality of tubular spark gap elements mounted in line with suitable apertures in said plate and electrically connected in series, and a fan arranged to move air through said casing to cool the gap elements.

In testimony whereof I have signed this specification in the presence of two subscribing witnesses.

FRITZ LOWENSTEIN.

Witnesses:
P. B. PHILIPS,
CHRISTY CROWLEY.

Copies of this patent may be obtained for five cents each, by addressing the "Commissioner of Patents, Washington, D. C."

O. J. AND L. LODGE.

OBTAINING OF UNIDIRECTIONAL HIGH TENSION DISCHARGES.

APPLICATION FILED DEC. 13, 1913.

1,307,742. Patented June 24, 1919.

Fig. 1.

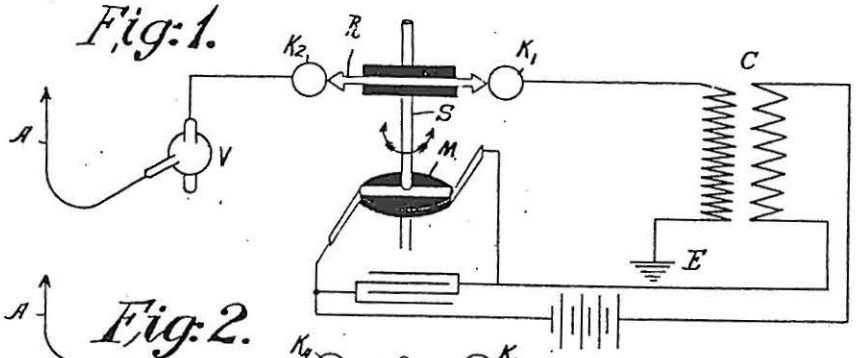


Fig. 2.

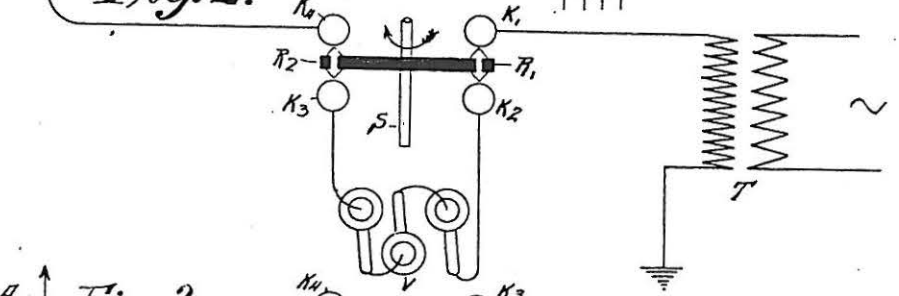


Fig. 3.

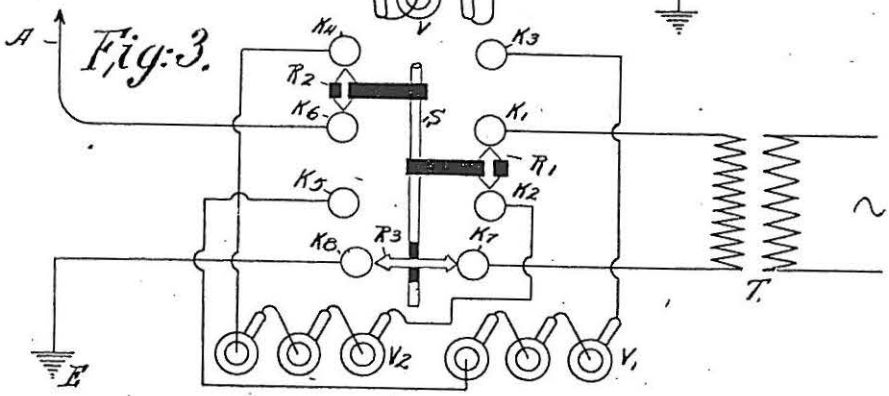
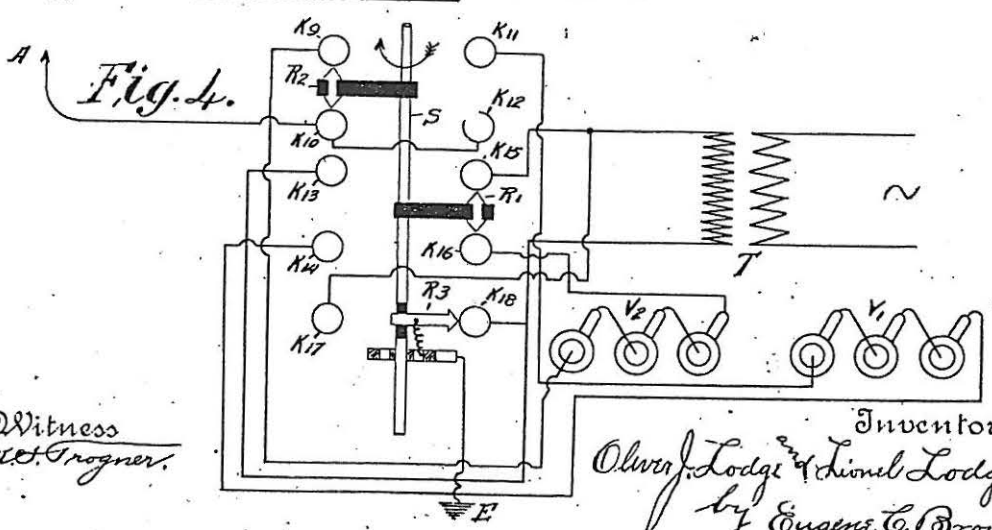


Fig. 4.



Witness
A. C. Trogner.

Inventor
Oliver J. Lodge and Lionel Lodge
by Eugene C. Brown
Attorney

UNITED STATES PATENT OFFICE.

OLIVER JOSEPH LODGE AND LIONEL LODGE, OF EDGBASTON, BIRMINGHAM, ENGLAND.

OBTAINING OF UNIDIRECTIONAL HIGH-TENSION DISCHARGES.

1,307,742. Specification of Letters Patent. Patented June 24, 1919.

Application filed December 13, 1913. Serial No. 806,600.

To all whom it may concern:

Be it known that we, OLIVER JOSEPH LODGE, knight, and LIONEL LODGE, both subjects of the King of Great Britain, both residing at Mariemont, Edgbaston, Birmingham, in the county of Warwick, England, have invented new and useful Improvements in the Obtaining of Unidirectional High-Tension Discharges, of which the following is a specification.

Unidirectional high potential discharges such as are required for the operation of Röntgen tubes, for dispersing fog, precipitating fume or other small particles, or for stimulating the growth of plants, are commonly obtained either from an alternator connected with a step-up transformer, or from a Ruhmkorff coil. In order that the discharges may be unidirectional it is necessary to suppress or reverse one half of each wave of alternating current given by the transformer, and in the case of an induction coil there is also an inverse E. M. F. on the making of the circuit which requires to be suppressed or reversed. As a rule the desired effect is obtained by introducing into the secondary circuit of the transformer or induction coil, a vacuum valve,—*i. e.* a vacuum tube so designed that current can pass through it freely only in one direction,—or a mechanical interrupter or commutator. Either of these devices may be arranged to enable both halves of the alternating current wave to be used. For this purpose in the case of the vacuum valve, four such valves are connected in a Wheatstone bridge network, with the source of supply in the position of the battery, and the consuming device in the position of the galvanometer; with interrupters a similar effect is obtained by using two double interrupters, one of which makes connection at the moment when the other breaks, the two, however, making connection in opposite directions.

A mechanical interrupter does not altogether prevent backward surging from the consuming device, while valves become gradually hardened by the repeated application of the inverse E. M. F. which they have to resist.

According to the present invention, therefore, these two devices are combined, so that the valve may be relieved by the interrupter from the stress of the inverse E. M. F.; and may supplement and be supplemented by the interrupter in stopping backward discharge. For this purpose a mechanical interrupter, which may be rotary or vibratory, and the effect of which is to interpose an air gap or other insulating material or a high resistance into the circuit, is arranged in series with a valve, for instance of the type described in British Patent No. 25047 of 1905. The interrupter is driven in synchronism with the interrupter of the induction coil or with the alternating current supply as the case may be, so as to break the circuit when the applied E. M. F. changes sign or falls below that in the work circuit.

Preferably the interrupter should operate two breaks for each set of valves so as to separate the valves not only from the source of supply but also from the consuming device during the desired interval.

If desired the apparatus may be duplicated so as to make use of both the direct and the inverse waves of current the interrupter being correspondingly modified so as to disconnect the valves which permit current to pass in one direction, while those which permit current to pass in the opposite direction remain in circuit.

The accompanying drawings show diagrammatically how the invention may be put into practice.

Figure 1 illustrates the invention in a simple form applied to an induction coil.

Fig. 2 is a better form adapted to isolate the valves applied to a transformer;

Fig. 3 shows an arrangement which may be used for dividing the current obtained from the transformer between separate sets of valves, and

Fig. 4 shows an arrangement in which Fig. 3 is so modified as to enable both halves of the wave of alternating current to be utilized in the D. C. circuit.

In Fig. 1, C indicates an induction coil the primary of which is supplied in the usual manner from a battery through an interrupter M shown as of the rotary type. One terminal of the secondary of the induction coil may be earthed and the other is connected through a mechanical interrupter and valve to a conductor A leading to the high tension apparatus for which a unidirectional discharge is required as, for example, a Röntgen tube. The mechanical interrupter requires to be driven in synchronism with the interrupter M and is indicated as a conductor R carried by the shaft S of the interrupter M and adapted twice in a revolu-

tion to bridge between the terminals K_1, K_2 so as substantially to complete a circuit between them. V is a vacuum valve connected in series with this interrupter. The conductor R should be so arranged with reference to the interrupter M as to bridge between the terminals K_1 K_2 at the moment when the secondary current due to the demagnetization of the core of the induction coil is passing and should be more or less transverse to the gap so as to interpose a maximum thickness of air or other insulation at the instant when the inverse E. M. F. due to make is generated. Thus the valve V is relieved from withstanding the inverse E. M. F.

In the construction of Fig. 2 the interrupter is arranged to produce a double gap so as completely to isolate the valves except when a discharge is passing through them. The apparatus is indicated as applied to a transformer T the primary of which will receive its current from an alternating source so that no interrupter in the primary circuit is needed. The interrupter in the secondary circuit consists of an insulating bar upon a rotating shaft S carrying two conductors R_1 R_2 adapted in turn to bridge the gaps between pairs of terminals K_1 K_2 and K_3 K_4 so as twice in a revolution substantially to complete a circuit through a group of valves V. The shaft S must be driven at a rate depending on the frequency of the primary supply, at a half synchronous speed, so that the completion of the circuit occurs only at instants of say maximum positive E. M. F. so that the intervening negative waves of E. M. F. are not applied to the valves at all and the current they would send is wholly suppressed. Moreover the valves are completely isolated even from the work circuit A except about the time of useful discharge, the advantage of this being that if A is maintained at a high potential, the valves have not the strain of this pressure constantly trying to leak back through them.

The current which the valves can pass without becoming overheated is limited. With a single set of valves therefore it is sometimes impossible to load a transformer or induction coil fully. The current may, however, be distributed between a plurality of sets of valves by the use of a duplicate apparatus such as is illustrated in Fig. 3. The interrupter shaft S here carries two insulating arms bearing conductors R_1 R_2 respectively. The conductor R alternately connects the terminals K_1 K_2 and the terminals K_3 K_6, and the conductor R_2 the terminals K_4 K_5 alternately with the terminals K_1 K_3. There is a set of valves V_1 permanently joined between the terminals K_3 K_5 and another set of valves V_2 permanently joined between the terminals K_2 K_4. There may be a conductor R_3 carried by the shaft S which bridges between terminals K_7 K_8 twice in a revolution. From inspection of the figure it will be seen that the secondary winding of the transformer T is connected twice in a revolution between the earthed point E and the work circuit A, on one occasion (viz. at the instant illustrated) through the valves V_2 and half a revolution later through the valves V_1. The valves which at any instant are not in use are completely isolated, as may be seen from a consideration of valves V_1 in the figure. In this construction the shaft S should run at half synchronous speed so that alternate positive half waves say, are sent through each set of valves, while the negative half waves are suppressed altogether.

By using a multiple of the revolving switch shown the current may be distributed through a greater number of sets of valves. For instance, the structure of Fig. 3 may have four sets of terminals instead of two so that circuits would be completed every quarter revolution instead of every half. The shaft S would then be rotated at one quarter a synchronous speed and four sets of valves could be employed, each set taking every fourth positive impulse.

If it is desired to use both the positive and negative half waves of E. M. F. the interrupter of Fig. 3 may be readily modified for this purpose, and one example of this modification is shown in Fig. 4.

The central spindle S, which in this case has to be driven at synchronous speed, carries the two insulating bars with conducting end pieces R_1 and R_2 as before, but the earthing conductor R_3 at the bottom is slightly modified as shown. There are two positions for the device. In that shown one terminal of the secondary of the transformer T, viz. the bottom terminal, is earthed through contact K_{18} and conductor R_3 through a slip ring and brush below. The upper terminal of the transformer is connected through contact K_{15}, conductor R_1, contact K_{16} to the set of vacuum valves V_2, and so on to contact K^9, conductor R^2, contact K_{10} to the consuming circuit.

In the alternative position of the device after the spindle S has turned through half a revolution the actions are reversed. The upper terminal of transformer T is earthed through contact K_{17} and arm R_3 as before. The lower terminal is connected through conductor K_{13}, conductor R_1, contact K_{14} to the set of valves V_1, and thence through contact K_{11}, conductor R_2, contact K_{12} to the work circuit. In one position the positive half waves are converted and passed on, and in the other position the negative half waves are utilized, the two sets of valves V_1 and V_2 being used alternately.

Alternatively a multiple switch may fulfil

both functions of rectifying and of distributing current through sets of valves. For instance where there are four sets of valves, two sets may take alternate positive impulses and the other two sets alternate negative impulses.

Obviously instead of multiplying the terminals the number of arms carrying conductors could be increased.

It is to be understood that the systems of connection described illustrate and do not delimit the scope of application of the invention.

What we claim is:-

1. The combination with a source of high electro-motive force and a work circuit adapted to operate at the upper portion of the current wave, of a vacuum valve, and mechanical means interposed between said source and said work circuit in series with said vacuum valve for breaking the circuit therethrough during periods of stress upon the valve at potentials lower than that of said work circuit.

2. Apparatus for producing high tension discharges comprising a source of high electromotive force, a work circuit, a vacuum valve interposed between said source and said work circuit, and a mechanical interrupter in series with said valve and adapted to interrupt the circuit in two places one on each side of the vacuum valve.

3. The combination with a source of high electromotive force and a work circuit of a plurality of vacuum valves or sets of vacuum valves, and mechanical interrupters interposed between said source and said work circuit, said interrupters operating to connect said valves or sets of valves in succession between said source and said work circuit during periods of maximum stress and to disconnect the valves during periods of lower stress.

4. In combination, a source of alternating E. M. F., a work circuit, sets of vacuum valves, terminals arranged in pairs and connected respectively to said source, said work circuit and said sets of valves, and a rotating shaft carrying a plurality of arms bearing conductors adapted to connect respective pairs of terminals at one point in their revolution and different pairs of terminals at another point in their revolution so as to join said valves in succession between said source and said work circuit.

In testimony whereof we have signed our names to this specification in the presence of two subscribing witnesses.

OLIVER JOSEPH LODGE.
LIONEL LODGE.

Witnesses:
NEUCOME TUCKERMAN,
ERNEST HARPER.

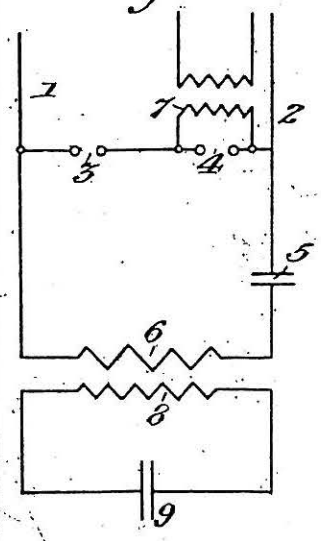
A. MEISSNER.

MEANS FOR PRODUCING SLIGHTLY DAMPED OSCILLATIONS BY SHOCK EXCITATION.

APPLICATION FILED JUNE 7, 1910.

1,077,733. Patented Nov. 4, 1913.

Fig. 3



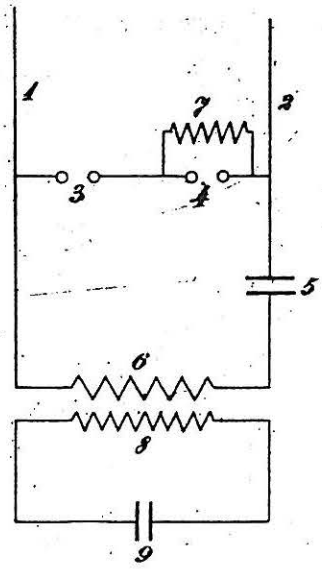
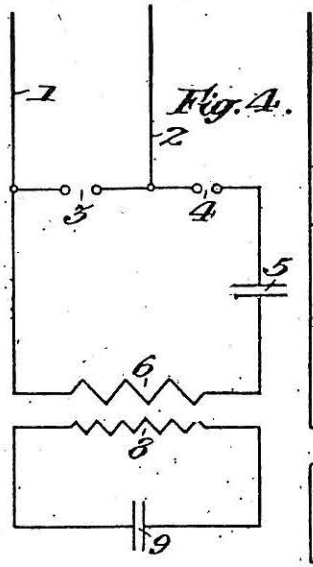


Fig. 1.

Fig. 4.



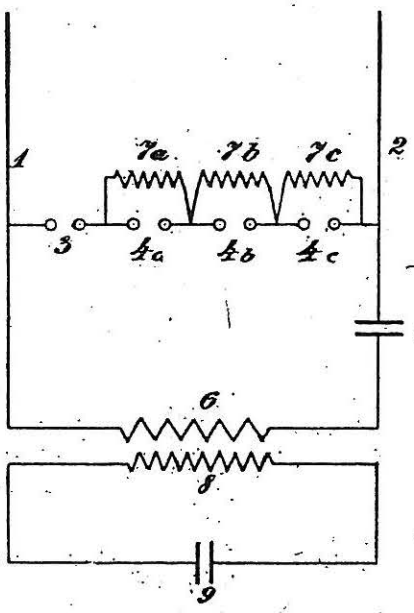


Fig. 2.

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Ray J. Ernst.

INVENTOR
Alexander Meissner
by his attorneys
Fisher & Brown

UNITED STATES PATENT OFFICE.

ALEXANDER MEISSNER, OF BERLIN, GERMANY, ASSIGNOR TO GESELLSCHAFT FÜR DRAHTLOSE TELEGRAPHIE, M. B. H., OF BERLIN, GERMANY, A CORPORATION OF GERMANY.

MEANS FOR PRODUCING SLIGHTLY-DAMPED OSCILLATIONS BY SHOCK EXCITATION.

1,077,733. Specification of Letters Patent. Patented Nov. 4, 1913.

Application filed June 7, 1910. Serial No. 565,558.

To all whom it may concern:

Be it known that I, ALEXANDER MEISSNER, a subject of the German Emperor, and residing at Berlin, Germany, have invented certain new and useful Improvements in Means for Producing Slightly-Damped Oscillations by Shock Excitation, of which the folowing is a specification.

My invention relates to means for producing slightly dampened oscillations with the aid of a primary oscillation circuit, to which current impulses are imparted and means acting upon some of the spark gaps of this circuit in such manner that the gaps do not limit the charging tension.

In arrangements for producing quenched sparks, such as in Wien's system, arrangements employing mercury vapor lamps or the like, which consist, as is well known, of two circuits coupled with each other in suitable manner and tuned to each other, there are limits both for the maximum admissible energy per spark and for the degree of coupling between the quench gap circuit and the secondary circuits which should not be exceeded, for otherwise the quench effect if present at all is obtained only imperfectly.

The principal object of my invention is to provide a connection for facilitating the quench effect of spark-gaps, in order to be able either to employ closer degrees of coupling when the usual quench gaps are used and to increase the energy per spark, or to employ spark-gaps which do not otherwise quench, to obtain the quench effect. The new connection simultaneously admits of the succession of sparks being increased beyond the limits customary heretofore, because owing to the sparks being more rapidly quenched the resistance in the spark gaps rises more rapidly and consequently the time during which the spark-coil or transformer is short-circuited is shortened. This end is substantially attained by interpolating in the primary oscillation circuit which I shall call hereafter the quench gap circuit an additional spark-gap having a high-frequency current resistance connected therewith in parallel, if necessary, but in any event so, that it does not limit the charging voltage. By high frequency current resistance the art understands nowadays means which offer a high resistance to high frequency currents only, but which not necessarily also constitute resistances for low frequency currents. For instance, a coil which may have a practically negligible inductance in low frequency circuits may offer a considerable resistance to the current in a high frequency circuit. These means may for instance also be ohmic resistances or condensers or the like, and their function will be explained in detail hereinafter.

All quench spark-gaps known heretofore, whether constructed as short Wien spark-gaps, as mercury-vapor lamps, as quench tubes or otherwise, have a twofold duty to perform in the connection in which they were used heretofore. First, before the spark occurs they serve for limiting the charging of the condenser, second after the spark is formed they aid the quenching of it, because the resistance of the discharging gap is rapidly increased by the continuous delivery of energy to the secondary circuit. According to my invention these two duties are separated. One spark-gap serves, as usual, for limiting the voltage for starting the sparks, but together with the additional spark-gap it serves for causing them to be rapidly quenched.

Some illustrative embodiments of my invention are represented in the accompanying drawing, wherein:

Figure 1 shows the use in connection with an ordinary oscillatory circuit of a supplementary spark gap bridged by an inductance. Fig. 2 shows a plurality of such supplementary spark-gaps in such a circuit. Fig. 3 shows an arrangement similar to that in Fig. 1, wherein the choking coil 7 forms the secondary of a spark coil. Fig. 4 shows an arrangement similar to that in Fig. 1, wherein the feeder 2 is arranged between spark-gaps 3 and 4.

Referring firstly to Fig. 1, 1 and 2 designate the charging feeders, 3 denotes the main spark-gap, 6 the primary coil of a transformer, 5 the condenser of the quench circuit, 4 an additional spark-gap, 7 a high frequency resistance, for instance a choking coil connected in parallel with the latter, 8 the secondary transformer coil, coupled with coil 6, and 9 the capacity of the tuned secondary circuit which is generally formed as an aerial for the purpose of radioteleg-

raphy. During the charging operation, the additional spark-gap 4 is practically short-circuited by the choking coil 7, so that the charging tension is limited solely by the spark gap 3. When the tension at which the gap 3 is broken down is reached and the spark occurs, this gap becomes conductive and the potential of conductor 1 is now directly at one of the electrodes of gap 4, and thus also at the corresponding end of the high frequency resistance 7. The other electrode of gap 4 and the corresponding end of resistance 7 were connected before with the other side of the condenser, and therefore the potential of that condenser side exists already at that side of gap 4 and of the resistance. From this it will be seen that at the moment gap 3 is broken down the total tension is transferred to gap 4, and the high frequency resistance 7. The latter has the effect that the potential difference can not be equalized immediately and since this difference is greater than the tension at which gap 4 commences to break down, the gap will be broken down immediately. The difference in time between the breaking down of gaps 3 and 4 would be difficult to measure on account of the rapid succession in which these two gaps break down. From the foregoing, it will be noted that this function of the high frequency resistance as characterized before may be performed by any kind of resistance, which is large enough to prevent the immediate equalizing of the potential difference between the two electrodes of gap 4, and aside from inductances and capacities, also ohmic resistances have been successfully used for this purpose. When thus as explained above gap 4 has been broken down choking coil 7 is practically cut out of circuit, and the quench gap circuit consists of the transformer coil 6, capacity 5 and the two spark-gaps 3 and 4. The choking coil 7 or its equivalents, as defined above, must be proportioned in the arrangement according to Fig. 1 only for a quite small strength of current, because it is not traversed by large currents either during charge or discharge. High frequency resistance 7 may be formed as the secondary coil of a spark-coil, as shown in Fig. 3, wherein 7 is the secondary and 10 the primary coil of an inductorium. In this event the discharge can be brought about by the latter. Under certain circumstances the spark-gaps 3 and 4 may be ordinary spark-gaps. But the efficiency of the entire arrangement is considerably increased when either the one or the other or both are formed as quench spark-gaps.

The feeder 2 can be connected equally well between the spark-gaps 3 and 4 without changing the effect of the arrangement. In this event the choking coil 7 may be done away with if the additional spark-gap 4 be sufficiently small as compared with the spark-gap 3. This arrangement is shown in Fig. 4, wherein the reference numerals are the same as in Fig. 1.

The quench effect is particularly increased when, instead of one additional or auxiliary spark-gap and a high frequency resistance connected in parallel therewith, several such combinations are connected in series. Fig. 2 shows such an arrangement as an example. In this figure, 1 and 2 designate the charging feeders, 3 is the main spark-gap, 4^a, 4^b, 4^c are the additional spark-gaps, 5 designates the capacity, and 6 denotes the transformer coil of the extinguishing circuit; 7^a, 7^b, 7^c are choking coils, or one choking coil having branches, arranged in parallel with the additional spark-gaps. The tuned secondary circuit is formed by the transformer coil 8 and the capacity 9. It will be noted that in this case, where each of the several spark gaps has its high frequency resistance, the gaps are broken down consecutively since one after the other receives the entire potential of the condenser.

In the arrangement according to Fig. 1 the disruptive voltage of the additional spark-gap 4 may be greater, than that of the main spark-gap 3, when the choking coil 7 is suitably dimensioned. In the arrangement according to Fig. 2, each individual spark-gap 4^a, 4^b, 4^c may be larger than or approximately as large as the main spark-gap.

By suitably dimensioning the starting tension of the auxiliary spark-gaps 4 or 4^a, 4^b, 4^c it is possible to obtain a maximum transmission of energy from the quench circuit to the secondary circuit, exactly as this was obtained heretofore by a suitable selection of the coupling between the quench and secondary circuits.

In the annexed claims I have referred to the spark gaps 3 and 4, described hereinbefore, as "two kinds of gaps." By the term "kind" I mean to convey the idea that these gaps have different characteristics, so far as their function in the circuit is concerned, as explained before, and as also explained in the subsequent portions of the claims. The term "kind" is not to be understood, however, to imply two kinds of gaps which are constructively different from each other, though as also explained hereinbefore I may use for both gaps 3 and 4 quench gaps, or also only for one a quench gap and for the other an ordinary gap, so long as their above defined characteristics are only of a different kind.

What I claim is:

1. An arrangement for producing slightly dampened electrical oscillations by shock excitation, comprising a primary oscillation circuit, containing a capacity, a self-induc-

No. 829,934. PATENTED AUG. 28, 1906.

F. K. VREELAND.

APPARATUS FOR THE PRODUCTION AND UTILIZATION OF UNDAMPED OR SUSTAINED ELECTRICAL OSCILLATIONS.

APPLICATION FILED NOV. 14, 1905.

4 SHEETS—SHEET 3.

Fig. 15

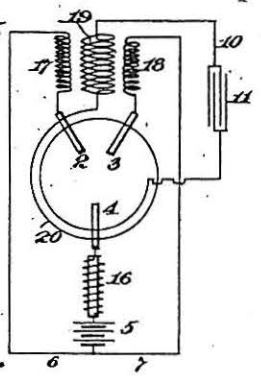


Fig. 16

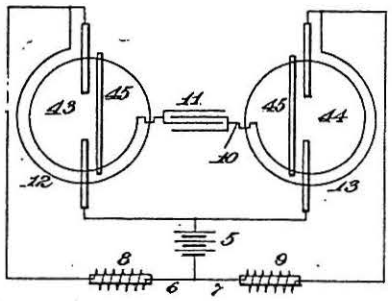


Fig. 17

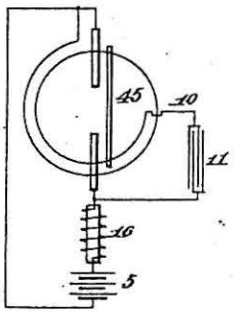


Fig. 18

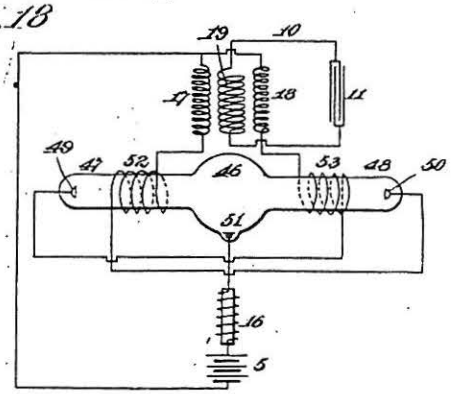


Fig. 19

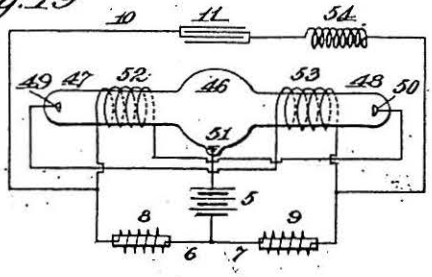
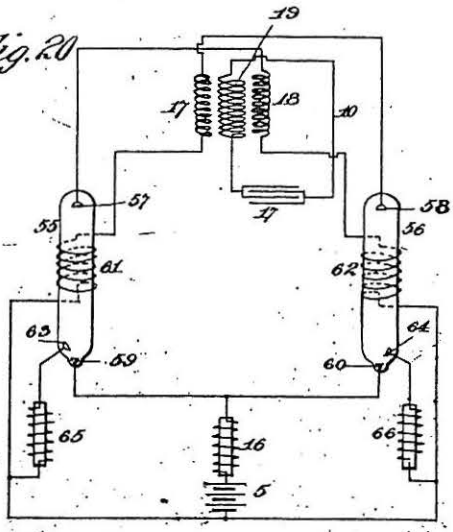


Fig. 20



Witnesses:

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John Botsch.

Inventor

Frederick K. Vreeland

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Attorneys.

No. 829,934. PATENTED AUG. 28, 1906.

F. K. VREELAND.

APPARATUS FOR THE PRODUCTION AND UTILIZATION OF UNDAMPED OR SUSTAINED ELECTRICAL OSCILLATIONS.

APPLICATION FILED NOV. 14, 1905.

4 SHEETS—SHEET 2.

Fig. 7

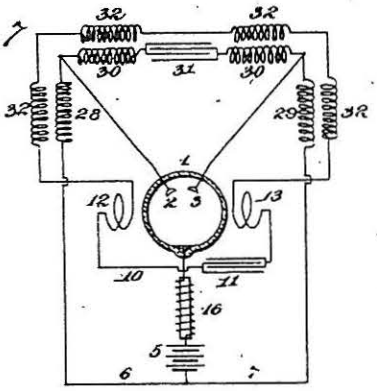


Fig. 8

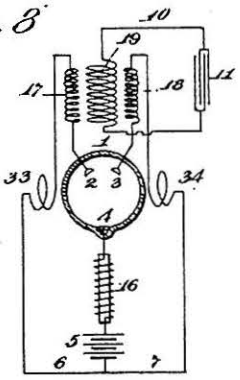


Fig. 9

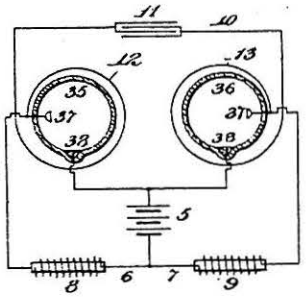


Fig. 10

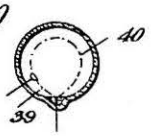


Fig. 12

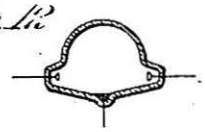


Fig. 11

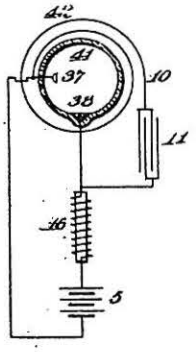


Fig. 13

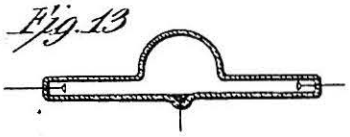
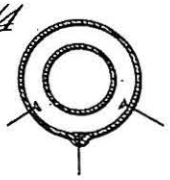


Fig. 14



Witnesses:

Jas. F. Coleman

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No. 829,934. PATENTED AUG. 28, 1906.

F. K. VREELAND.

APPARATUS FOR THE PRODUCTION AND UTILIZATION OF UNDAMPED OR SUSTAINED ELECTRICAL OSCILLATIONS.

APPLICATION FILED NOV. 14, 1905.

4 SHEETS—SHEET 1.

Fig. 1

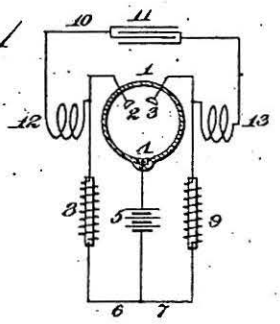


Fig. 2

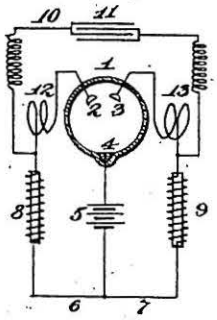


Fig. 3

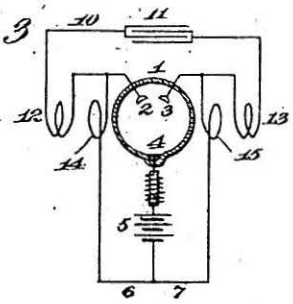


Fig. 4

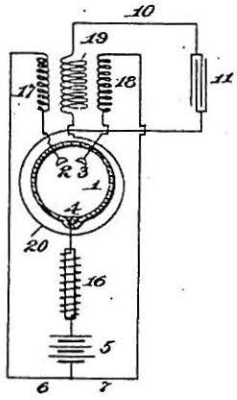


Fig. 5

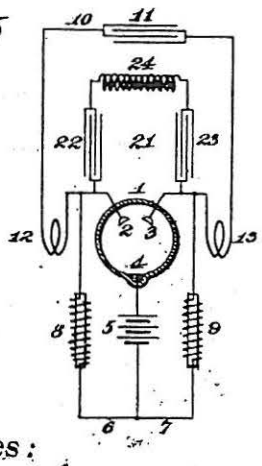
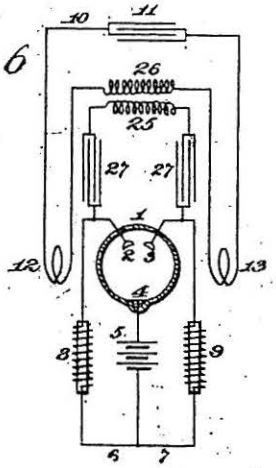


Fig. 6



Witnesses:

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No. 829,934. PATENTED AUG. 28, 1906.

E. K. VREELAND.

APPARATUS FOR THE PRODUCTION AND UTILIZATION OF UNDAMPED OR SUSTAINED ELECTRICAL OSCILLATIONS.

APPLICATION FILED NOV. 14, 1905.

4 SHEETS—SHEET 4.

Fig. 21

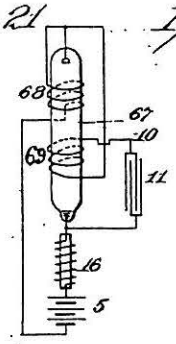


Fig. 22

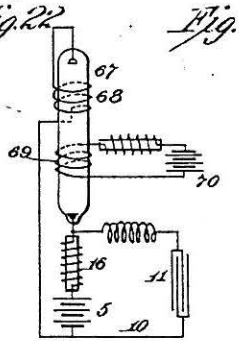


Fig. 23

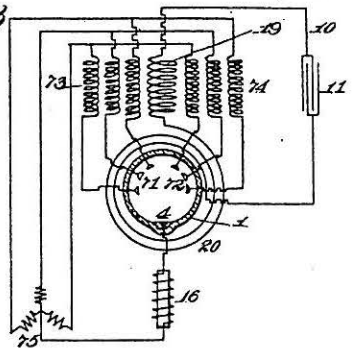


Fig. 24

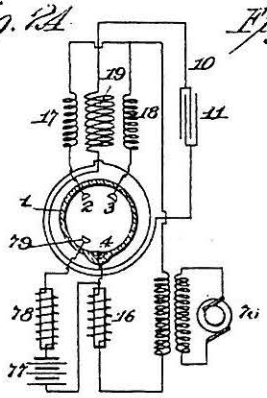


Fig. 25

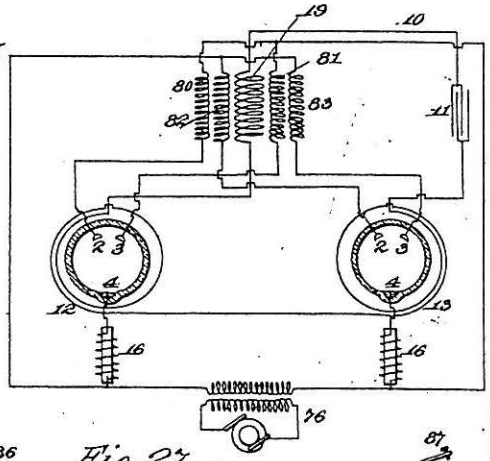


Fig. 26

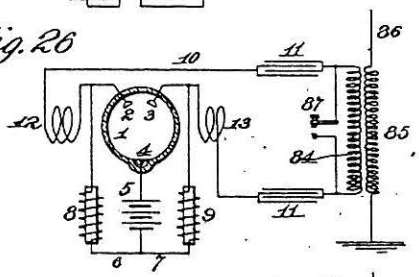


Fig. 27

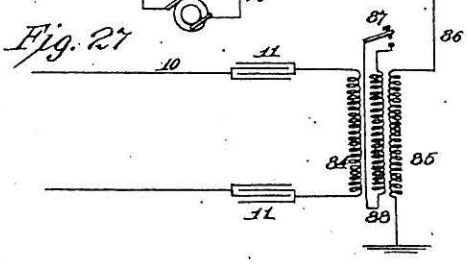


Fig. 28

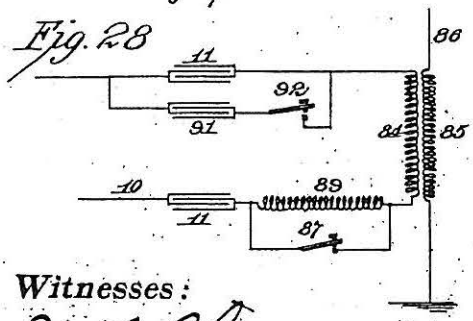
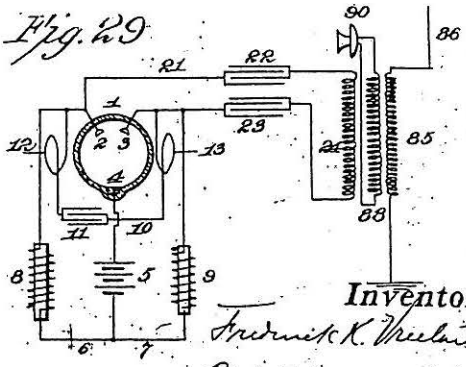


Fig. 29



Witnesses:

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Frederick K. Vreeland

By Dyer & Dyer,

Attorneys.

UNITED STATES PATENT OFFICE.

FREDERICK K. VREELAND, OF MONTCLAIR, NEW JERSEY, ASSIGNOR TO WIRELESS TELEGRAPH EXPLOITATION COMPANY, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK.

APPARATUS FOR THE PRODUCTION AND UTILIZATION OF UNDAMPED OR SUSTAINED ELECTRICAL OSCILLATIONS.

No. 829,934. Specification of Letters Patent. Patented Aug. 28, 1906.

Original application filed February 28, 1905, Serial No. 247,826. Divided and this application filed November 14, 1905. Serial No. 287,223.

To all whom it may concern:

Be it known that I, FREDERICK K. VREELAND, a citizen of the United States, residing at Montclair, in the county of Essex and State of New Jersey, have invented a certain new and useful Apparatus for the Production and Utilization of Undamped or Sustained Electrical Oscillations, of which the following is a description.

The object of this invention is the generation of undamped or sustained electrical oscillations of definite frequency, and especially alternating currents of high frequency, without the aid of mechanical translating devices.

Undamped oscillations of low frequency may be obtained by mechanical means, but the frequency is limited by practical considerations governing the design and construction of the apparatus. Oscillations of higher frequency are desirable for many purposes, as is well known, and especially for the production of electromagnetic waves for use in wireless telegraphy, wireless telephony, and for similar purposes. For this service low-frequency oscillations are unsuited owing to their small radiating power.

Where high-frequency currents are desired, it is usual to employ the free oscillations which may occur in a circuit containing capacity and inductance. A certain initial supply of energy is imparted to the oscillating system, by charging the condenser, for example, and this energy takes the form of alternating currents of a frequency determined by the electrical constants of the circuit, which alternating currents continue with constantly-decreasing amplitude until all the energy is expended in radiation or in ohmic and other losses. Such oscillations are thus always damped, and their usefulness is therefore greatly limited.

By the apparatus herein described, the free oscillations of an electrical circuit are also utilized, but these oscillations are sustained by feeding energy into the circuit constantly or at intervals in synchronism with the oscillations to supply that lost in radiation and otherwise, and thus the oscillations are maintained at a constant amplitude as long as the supply of energy continues. This I accomplish by employing the energy of the oscillating circuit to produce, directly or indirectly, opposite or synchronous effects upon a sensitive gap or gaps which will be so related to the oscillating circuit as to supply energy thereto and maintain the oscillations. This may be done by the effect of a magnetic field upon a current in a solid or liquid conductor or in a rarefied gas or upon an open or inclosed arc, or by the effect of an electrostatic field upon the discharge of cathode particles in a vacuum-tube, or by the diversion of magnetic flux by the cross magnetomotive force of an auxiliary field, or by the direct effect of an electric current on the conductivity of the circuit in which it flows, or by other means of electrically commutating energy. I prefer to employ the effect of a magnetic field upon a sensitive gap or gaps formed by the electric current passing through one or more vacuum-tubes, such as mercury-vapor tubes. This magnetic field may be directly excited or have its excitation controlled by the electrical oscillations of the oscillating circuit, and its effect upon the vapor tube or tubes will be, according to one or another arrangement, to divert the current passing through the sensitive gap or gaps or to vary the conductivity of such gap or gaps, so as to produce an electrical commutation of the current between different circuits which are related to the oscillating circuit, in such manner as to add energy thereto by this commutation in synchronism with the oscillations.

The invention may be carried out in many different ways and with a variety of forms of apparatus, some of which are illustrated in the accompanying drawings.

Figure 1 illustrates in diagram an arrangement which I have found effective. In this figure, 1 is a mercury-vapor tube, having anodes 2 3, and a mercury cathode 4. 5 is a source of direct current connected by two branches 6 7 with the anodes 2 and 3 respectively. These branches 6 and 7 include large inductances 8 9 for maintaining a steady current. 10 is the oscillating circuit, containing a condenser 11. This circuit is shunted across the anodes 2 3, and includes the field-coils 12 13. It should be understood that for simplicity of illustration the

field-coils 12 13 are shown with their axes in the plane of the anodes 2 3, while in practice they are placed in a plane perpendicular to that in which the anodes are located, so that the magnetic flux will be perpendicular to the plane of the anodes. In starting the apparatus, it is first necessary to establish the current across the sensitive gap formed by the tube 1. This may be done in any of the well-known ways. At the start the current tends to divide equally between the two parallel paths, but there is always some variation in the distribution due to variable inequalities in the conductivities of the two paths. This is especially true when a mercury-vapor tube is used. These irregular fluctuations are usually sufficient to start the oscillations, after which they give place to the periodic fluctuations controlled by the alternating field; but where an additional impetus is required, this may be supplied by giving the condenser a sudden initial charge, by short-circuiting one of the inductances 8 9 and then suddenly removing the short circuit, or by otherwise disturbing the equilibrium of the system. When the magnetic field deflects the current in the tube, say from the anode 2 to the anode 3, the tendency is for the current in both branches 6 and 7 to pass wholly or largely through the tube from the anode 3 to the cathode 4, due to the fact that the path through the tube from the anode 2 to the cathode 4 is interrupted or increased in resistance by the deflection of the current toward the anode 3. As the inductances 8 9 oppose any change in the current passing through them, this results in the current in the branch 6 flowing through the oscillating circuit 10 from left to right, including both field-coils 12 13, thereby producing a field which still further deflects the current from 2 to 3. When the condenser is charged to the requisite potential, this current is checked and reversed, thereby producing a field in the opposite direction which deflects the current in the tube from the anode 3 to the anode 2. The result of this deflection is to cause the current in both branches 6 and 7 to pass through the tube from the anode 2 to the cathode 4, which results in the current in the branch 7 flowing through the oscillating circuit from right to left and producing a current in the field-coils 12 13 which still further deflects the current from the anode 3 to the anode 2. In this way energy is supplied to the oscillating circuit in synchronism with the oscillations. The frequency of these oscillations is dependent upon the constants of the oscillating circuit and may be changed by changing such constants.

The field-coils, instead of being connected in shunt to the anodes of the tube, may be connected in series therewith, as illustrated in Fig. 2, which is a diagram of the same character as Fig. 1. In this arrangement the field-coils 12 and 13 are placed directly in the branch circuits 6 7 between the inductances 8 9 and the anodes 2 3, and the oscillating circuit 10 is completed through these coils by connecting that circuit with the branches 6 7 between the field-coils 12 13 and the inductances 8 9. Extra inductances may be placed in the oscillating circuit, as shown. When the magnetic field tends to deflect the current in the tube from the anode 2 to the anode 3, the current in the branch 6 will be deflected through the oscillating circuit from left to right and will energize the magnetic field, producing a field tending to still further deflect the current from the anode 2 to the anode 3. The reversal of the current in the oscillating circuit will energize the magnetic field in the opposite direction, deflecting the current in the tube from the anode 3 to the anode 2 and causing the current in the branch 7 to pass through the oscillating circuit from right to left, producing a still further energization of the magnetic field in the same direction.

Another arrangement is that illustrated in Fig. 3, which is a diagram similar to the figures already described, and in which a compound excitation of the magnetic field is provided. The oscillating circuit is shunted across the anodes, as in Fig. 1, and is provided with the field-coils 12 13, while additional field-coils 14 15 are located in the branches 6 and 7. The direction of winding of coils 14 and 15 is such that their fields oppose and neutralize each other when they are traversed by equal battery currents. When the magnetic field tends to deflect the current from the anode 2 to the anode 3, the current in the branch 6 passes through the oscillating circuit from left to right, energizing the coils 12 13. The current in the coil 14 diminishes somewhat, and that in the coil 15 increases, thus adding to the magnetic effect of coils 12 and 13. The resultant magnetic field tends to still further deflect the current to the anode 3. The reversal of the oscillating circuit reverses the field, deflects the current from anode 3 to anode 2, and causes the current in the branch 7 to flow through the oscillating circuit from right to left.

In Fig. 4 is shown a secondary series arrangement for the excitation of the field. A steadying inductance 16 is placed in the undivided portion of the battery-circuit. In the branches 6 and 7 are located oppositely-wound primary coils 17 18 of a transformer, of which 19 is the secondary. The secondary coil 19 is located in the oscillating circuit 10, and the field-coil 20 is located in the oscillating circuit. The field-circuit is shown in this figure as in its proper relation to the plane of the anodes. The primary coils 17 18, being similar but being wound in opposite directions, an increasing current in 17 will have the same effect on the secondary 19 as a decreasing current in 18. The oscillating cur-

rent in the circuit 10 will deflect the current in the tube from one anode to the other, so that the current from the battery will flow alternately in the two primary coils 17 and 18 of the transformer, and these variations in the primary current acting cumulatively on the secondary 19 induce in the secondary the electromotive force necessary to overcome resistance and other losses and sustain the oscillations in the oscillating circuit 10. Either primary coil 17 18 may be used alone to excite the oscillating circuit, or each may act upon a separate oscillating circuit.

Many modifications of the arrangements shown in Figs. 1 to 4 may be employed.

In Fig. 5 an arrangement similar to Fig. 1 is shown, with the addition of another shunt-circuit 21, connected across the anodes 2 3, and containing condenser 22 23 and an inductance 24, forming an additional oscillating circuit. If the two oscillating circuits are tuned in unison, they will oscillate in parallel, and the circuit 21 may be used as the working circuit, while the circuit 10 serves only to excite the field. If the two oscillating circuits are not exactly in tune, there will be a wattless component of current leading in one circuit and lagging in the other according as the capacity reactance or the self-induction reactance preponderates. Thus by varying the constants of the two circuits any desired phase relation may be secured between the current in the field-coils and the terminal electromotive force across 2 and 3, though usually it is desirable to have the electromotive force and the current in phase with each other.

In Fig. 6 is shown an arrangement in which the field-coils 12 13 are located in the oscillating circuit 10 connected inductively through the transformer 25 26 to the primary circuit. The primary 25 of the transformer is shunted across the anodes 2 3 and includes one or more condensers 27. The condenser or condensers 27 permit the tuning of the primary circuit with respect to the secondary.

In Fig. 7 is shown an arrangement combining certain features of Figs. 4 and 6. The primaries 28 29 of a transformer are connected in series with the anodes 2 3, and a third primary 30, which may also include a condenser 31, is shunted across the anodes 2 3. The secondary coil 32 is acted on cumulatively by all three of the primaries, and includes in its circuit the field-coils 12 13 and the condenser 11.

Fig. 8 illustrates an arrangement similar to Fig. 4, but with the field-coils located in the primary instead of in the secondary circuit. The secondary current serves to control the frequency of the field through the action of the secondary 19 on the primaries 17 18. The field-coil is divided into two sections 33 34 located respectively in the circuits 6 7. These field-coils are wound in opposite directions, so that their magnetic fields will oppose and neutralize each other when the current is divided equally between the circuits 6 7. When, however, there is an unequal distribution of current in these circuits, the field produced by one coil will predominate over that produced by the other, and will cause the current to be deflected to one or the other of the two anodes, as in the case illustrated in Fig. 4.

Instead of using a single vapor-tube with two anodes, two asymmetrical vapor-tubes 35 36 may be employed, as illustrated in Fig. 9. Each of these tubes has an anode 37 and a mercury-cathode 38, the anode of each tube being located at one side of the tube close to the cathode, so that when the current is diverted by the magnetic field toward the anode, the current will flow in a short path from the anode to the cathode, while if the current is deflected away from the anode, the current will follow a longer path and one of greater resistance. The arrangement of circuits for exciting the magnetic field shown in Fig. 1 is selected for illustration in Fig. 9, but any other arrangement may be employed. The cathodes of the two tubes are connected together and with a source 5 of direct current. The circuit is divided into two branches 6 7, including large inductances 8 9, and these branches 6 7 extend to the anodes of the two tubes. The oscillating circuit 10, including the condenser 11, is shunted across from one anode to the other, and includes the field-coils 12 13, one of which surrounds the tube 35 and the other the tube 36. The field-coils 12 13 affect the tubes 35 36 oppositely. When the current in the oscillating circuit 10 flows in one direction, it deflects the current in the tube 35 away from the short path between the anode and cathode, increasing the resistance of the path through which the current flows, while in the tube 36 the field deflects the current toward the short path between the anode and the cathode, thus giving the minimum resistance in this tube. The result of this is to cause the larger part of the current in the branch 6 to flow through the oscillating circuit from left to right, strengthening the fields in the direction to augment their effect upon the tubes. A reversal of the current in the oscillating circuit reverses the fields, and causes the path in the tube 36 to lengthen and increase in resistance, and the path in the tube 35 to shorten and decrease in resistance, with the result that the current in the branch 7 passes largely through the oscillating circuit from right to left, adding energy to the oscillating circuit and increasing the strength of the current in the field-coils.

The shifting of the current between paths of different lengths and resistances is illustrated in Fig. 10, in which the dotted line 39

illustrates the path that the current will take through the tube when the polarity of the magnetic field is such as to deflect the current toward the anode, while the dotted line 40 shows the path that the current will take through the tube when the polarity of the field is reversed. The increased current-density in the short path tends to still further increase its conductivity under suitable conditions.

A single asymmetrical tube may be employed to produce the electrical commutation of the current between two circuits, as illustrated in Fig. 11, in which the tube 41 is provided with the single anode 37 and the mercury cathode 38 placed close together on one side of the tube. The oscillating circuit 10, including the condenser 11, is shunted across the anode and cathode, and includes the field coil 42 surrounding the tube. The anode and cathode are also connected by another circuit, includng the source of direct current 5 and a steadying inductance. A plus current, for illustration, in the oscillating circuit and the field-coil will deflect the discharge through the tube to the right, or cause it to follow the path of great length and resistance illustrated by the line 40 in Fig. 10. Since the battery current is made constant by the inductance, the increase in resistance of the path through the tube will force part of the current to pass through the oscillating circuit in shunt to the tube, and will increase the deflection of the current in the tube to the right, thus forcing more current through the oscillating circuit. When the condenser 11 is charged to a certain limiting point, its electromotive force will prevent a further flow of the current in this direction, and the current in the oscillating circuit will reverse, causing a deflection of the discharge to the left, or to the short path 39 shown in Fig. 10. This reduces the resistance of the path through which the current passes in the tube, and allows an increase of current from the anode to the cathode, and a corresponding increase in the minus current in the oscillating circuit. The oscillations will thus be maintained.

The mercury-vapor tube may be of a variety of forms, and preferably is one of sufficient size to give a considerable body of vapor for keeping the tube cool and the vacuum high during the operation of the apparatus. As illustrated in Fig. 12, it may be a tube of a substantially spherical shape, with the two anodes and cathode in its bottom. Or, as illustrated in Fig. 13, the anodes may be located at the ends of lateral tubes extending in opposite directions from the base of a chabmer, these lateral tubes increasing the resistance between the anodes and the cathode, and also increasing the potential necessary to operate the tube. Or, as shown in Fig. 14, the tube may be a ring—a construction which will give a wide defference in resistance between the short path from one anode to the cathode, and the long path from that anode to the cathode around the other side of the ring. A chamber could be added to the ring-tube, if desired, to increase its vapor capacity. The asymmetrical tube of Figs. 9 to 11 could be made in the form of any of these tubes with one of the anodes omitted or simply not utilized in making the circuit connections.

At the frequencies met with in ordinary alternating current practice, and even at very much higher frequencies, an ordinary open-air or inclosed arc may be used as the sensitive gap, such as is illustrated in Fig. 15, in which the parts are the same as described in connection with Fig. 4 except that the terminals 2, 3, and 4 of the vapor-tube are replaced by the carbon electrodes 2, 3, and 4 of an open or inclosed arc. Any of the other circuit arrangements described in connection with the vapor-tube having three terminals can be used with the three carbon electrodes.

Fig. 16 shows an arrangement in which a shunt oscillating circuit is caused to act upon two separate sensitive gaps similar to the arrangement shown in Fig. 9, but with electric arcs 43 44 substituted for the vapor-tubes. Adjacent to each arc is placed a block of carbon 45. A current in the field-coils 12 13 tends to deflect these arcs in opposite directions with respect to their carbon-blocks. Thus, the arc 43 is deflected toward its block and its conductivity is not seriously diminished, while the arc 44 is deflected into space and its conductivity decreases materially. These changes in conductivity are caused to excite the oscillations in the oscillating circuit 10 in a manner similar to that described with reference to Fig. 9.

With an arc such as illustrated in Fig. 16, conditions are secured similar to those secured with the asymmetrical vapor-tube of Figs. 9 to 11, and hence it follows that such an arc may be employed in an arrangement similar to that illustrated in Fig. 11. This arrangement is shown in Fig. 17.

In the forms of apparatus above described, the sensitive gaps used have included a gas as the sensitive medium, but it is not necessary that the sensitive medium be gaseous. Similar results may be obtained by the use of a liquid or solid medium—for example, the tubes which were described as containing mercury vapor may be filled with a conducting liquid, or instead of the mercury-vapor tube, a mass of solid material may be used having three terminals, the current entering through two of these terminals and leaving through the third, or vice versa. It is desirable to use a sensitive medium whose specific resistance is high, or to so construct the sensitive gap that the act of commutation is accompanied by a considerable difference of potential between the terminals of the sensi-

tive gap. This effect is promoted by the use of a gaseous medium which, under suitable conditions of pressure, temperature, and ionization, has the property of rapidly increasing conductivity with increasing current density, so that the effect of the concentration of current in a restricted path between one pair of electrodes is to greatly increase the conductivity of that path, while the conductivity of the other path is decreased. The result is a considerable potential difference available for exciting the oscillations. The effect of varying conductivity with varying current density may be in itself sufficient under proper conditions to maintain the oscillations. It is probable also that in a gaseous medium the direct effect of ionic bombardment of the anodes contributes largely to the useful result. It is evident, however, that the invention is not limited to any particular method of producing the electrical commutation, or dependent upon any special theory of operation.

In Fig. 18 is shown a form of apparatus in which the conductivity of the alternative parts is varied in a somewhat different manner. Instead of causing the discharge through the commutating-gap to be deflected by a magnetic field whose flux is perpendicular to the direction of the current, I utilize the fact that a magnetic field, even though its flux be parallel to the direction of the current, has the effect of diminishing the conductivity of the conducting-column of gas in a vacuum-tube. A vacuum-tube 46 is provided with two protuberances 47, 48, in the ends of which are sealed anodes 49, 50. A single cathode 51 is provided near the center of the tube. Field-coils 52, 53 are wound around the protuberances 47, 48, and are connected in the branches of the divided primary circuit, which include the primaries 17, 18 acting on the secondary 19 of the oscillating circuit 10. When the current divides equally between the two parallel paths through the tube, the gas columns in the protuberances 47, 48 will have approximately equal conductivities; but if the current in 52, for instance, is greater than that in 53, the conductivity of the gas column in the branch 47 of the tube is diminished and a still larger proportion of the current will be forced through the gas column in the branch 48. This increase of current in the branch 48, the field-coil 52 and the primary 17, and the corresponding decrease in current in the branch 47 with the field-coil 53 and the primary 18, continue until a practically steady state of unequal current distribution is reached, when the primaries 17, 18 cease to act on the secondary 19 and the current in the oscillating circuit 10 reverses. This induces an electromotive force in the primaries 17, 18 (now acting as secondaries to the coil 19,) which tends to decrease the current in the branch 48 and increase that in the branch 47, thus starting a disturbance of the equilibrium in the opposite direction, and this process is repeated, thus sustaining the oscillations. Another phenomenon which may be utilized in a tube of similar construction is the tendency of an axial field to concentrate a cathode-beam in the direction of the magnetic flux, thus directing it toward the two anodes alternately.

Figure 19 shows an arrangement embodying the same form of tube as that illustrated in Fig. 18, with connections similar to those shown in Fig. 1 in so far as the power-currents are maintained steady and the oscillating circuit is in shunt connection. The field-coils 52, 53 are wound and connected to their respective anodes 50 and 49, as in Fig. 18, and are connected respectively through the large steadying-inductances 8, 9 to one terminal of the source 5. The oscillating circuit 10 is connected in shunt across the coils 8, 9, so that any unequal distribution of current in the two branches of the tube will produce a current in the oscillating circuit, which is provided with an inductance 54. The current in the oscillating circuit is thus an alternating one, while the currents in the coils 52, 53 and their corresponding anodes 50 and 49 are pulsating currents. These pulsating currents have the effect of periodically diminishing the conductivity of the branches 47 and 48 of the tube alternately, as in the case illustrated in Fig. 18.

It is not necessary that the alternate paths should be included in the same tube. Fig. 20 shows an arrangement in which two separate tubes 55, 56 are used. These tubes have anodes 57, 58 and cathodes 59, 60, and are provided with field-coils 61, 62, which are connected at one end with one terminal of the direct-current source, and at their other ends are connected with the primary coils 17, 18, acting upon the secondary coil 19 in the oscillating circuit 10. Changes in the conductivities of the gas columns in the tubes 55, 56 will act in a manner similar to that described in reference to Figs. 18 and 19. In case the fields acting on the tubes are sufficient to completely interrupt the discharges, a set of auxiliary anodes 63, 64 may be provided, so placed as to be uninfluenced by the field, and connected through steadying inductances 65, 66 with the source of power. These auxiliary anodes will keep the cathode resistance broken down, so that the current through the main anodes 57, 58 will start again at the proper time. The steadying inductance 16 may then be omitted, if desired. A single tube of this character having only one anode may be employed to produce the oscillations. This is illustrated in Fig. 21, in which the tube 67 is provided with two field-coils 68, 69, the former being in series with the source of current 5 between the anode and the cathode, while the latter is in the oscillating cir-

cuit 10, which is shunted across the terminals of the tube. A plus current, for instance, in 69 will assist 68 and cause an increased plus current to flow in 69. A minus current in 69 will oppose 68 and improve the conductivity of the gas column and still further increase the minus current in 69. The periodic reversals of the oscillating circuit will, as already explained, produce the reversal of current in the coil 69.

In Fig. 22 the variable anode-current is used to excite the field 68. As its variations are just the opposite to what is required, an auxiliary field 69 fed by a constant source 70 is opposed to and is greater than 68. The differential effects of 68 and 69 give the required result.

An alternating current, either single phase or polyphase, may be used instead of a direct current to feed the apparatus. Fig. 23 shows the apparatus supplied by a three-phase current. 1 is the vapor-tube, having a single cathode 4, and provided with six anodes, three of which, 71, are located on one side of the tube, and the other three, 72, on the other side of the tube. These anodes are connected to separate primaries 73, 74 of a transformer, whose secondary 19 is located in the oscillating circuit 10 containing the condenser 11 and the field-coil 20. The primaries 73 are wound in the same direction, so that their effects on the secondary 19 are similar, and the primaries 74 are wound in the opposite direction. The primaries 73 and 74 are connected in parallel in pairs, and each pair of the primaries is in series in circuit with one phase of a three-phase alternating-current generator 75, whose neutral point is connected through the steadying-resistance 16 to the cathode 4 of the tube. The mode of operation of the apparatus is similar to that of the apparatus shown in Fig. 4. The vacuum-tube acts as a rectifier of the alternating current by permitting the current to flow only in one direction, *i. e.*, from one or more of the anodes to the cathode, the opposite half-wave being excluded; and the sum of the half-waves in the three phases is equivalent to a direct current of nearly steady value. The fluctuations of this equivalent direct current being of low frequency, will not have any appreciable effect on the secondary 19, but the deflection of the current from one of the anodes 71 to the corresponding anode 72 will produce an effect on the secondary similar to that which occurs in the case of the direct current in Fig. 4.

Fig. 24 shows the apparatus fed by a single-phase alternating current. In this case the tube 1 is provided with two anodes 2, 3, and the cathode 4, as in Fig. 4, the anodes being connected with the primaries 17, 18, which are connected in parallel with the source 76 of single-phase alternating current, the other pole of which is connected through the inductance 16 with the cathode 4. In this case the inductance 16 should be small enough to permit the ready passage of the alternating current from the source, or in some cases the inductance may be omitted altogether. As the single-phase alternating current when rectified by the tube 1 is discontinuous, it is necessary to supply means for starting the current through the tube at the beginning of each effective half-wave. To accomplish this, it is sufficient to keep the cathode resistance, which is high at starting, continuously broken down by means of a small electric current supplied by a local source 77 through a steadying-inductance 78 and an auxiliary anode 79. The alternating current will then start readily when the electromotive force is applied in the proper direction. When a single-phase alternating current is used, the supply of energy is intermittent; consequently the currents in the oscillating circuit 10 will be intermittent unless the damping of this circuit is so small that its oscillations may persist through the period of inactivity of the source. This feature possesses certain advantages when the apparatus is used as a transmitter in wireless telegraphy, as it causes the signals to be broken up into individual impulses recurring at the frequency of the alternating current, each impulse consisting of a train of waves of practically constant amplitude. Signals of this character are particularly desirable when the signals are received by ear, as an intermittent impulse gives a much stronger physiological effect than a continuous impulse. This feature is also advantageous in imparting a distinctive character to the radiations apart from their definite wave frequency, which enables them to be distinguished from signals from another source either audibly or by means of some automatic selecting apparatus.

A quarter-phase alternating current can be used in the same manner as a single-phase current by using two pairs of anodes and primaries instead of one; or it may be converted into a four-phase current in the well-known way, and used with four sets of anodes and primaries in a manner similar to that illustrated for three-phase currents in Fig. 23. In the former case the energy supply will be intermittent, and in the latter continuous though variable.

Whether the alternating-current supply be single phase or polyphase, it is desirable to have two sets of apparatus of the character illustrated in Figs. 23 and 24, having their polarities reversed with respect to the source of power. The second set of apparatus will then use the half-waves of the alternating current that are rejected by the first set. The two sets of apparatus may operate separate oscillating circuits, their respective primary coils being made to act on separate sec-

ondary coils, or they may be caused to act cumulatively on a single oscillating circuit. Fig. 25 shows an arrangement in which this is accomplished by causing the primary coils of the two systems to act on a single secondary. The case illustrated is that in which a single-phase alternating current is used. The primary coils 80, 81 of the first system are wound respectively in the same direction as the primaries 82, 83 of the second system, so that the two systems will act in the same sense and therefore cumulatively on the secondary 19, and the field-coils 12, 13 included in the oscillating circuit 10 are wound to have similar effects on the two tubes.

So far I have described only the method of and apparatus for producing the oscillations. They may be utilized in many ways; for example, in electrotherapeutics, in exciting high-frequency discharges in vacuum-tubes for lighting, in producing high potential effects through the agency of air core-transformers, and for many other purposes for which alternating currents, whether of extremely high or of lower frequencies, are desirable. They are especially useful in a transmitter for use in wireless telegraphy or wireless telephony. For this purpose the oscillating circuit may be coupled to a radiating antenna in any one of several well-known ways.

In Fig. 26 the oscillating circuit 10 is illustrated as supplied with energy by the arrangement of apparatus shown in Fig. 1. This oscillating circuit includes the primary 84 of a step-up transformer, whose secondary 85 is connected in series with the antenna-circuit 68, which is suitably tuned with respect to the primary circuit. The radiation is made intermittent at will for the purpose of producing signals by means of a key 87 which short-circuits the primary 84 of the step-up transformer and thus annuls its action on the antenna-circuit.

Another arrangement is shown in Fig. 27, in which the key 87 is placed in a tertiary circuit 88 of the step-up transformer. The closing of the key short-circuits the tertiary circuit and annuls the inductive effect of the primary 84 on the secondary 85.

In Fig. 28 the key 87 is placed so as to short-circuit an auxiliary inductance 89, placed in the oscillating circuit 10. In this arrangement the radiation of energy from the antenna is continuous, but its frequency is altered by the presence or absence of the auxiliary inductance 89 in the oscillating circuit, and the latter is thus thrown in or out of tune with the antenna-circuit and with the receiving apparatus, which is assumed to be tuned to respond only to a given frequency of the transmitter. Instead of throwing the oscillating circuit in and out of tune with the antenna by changing the inductance of the circuit, the same result may be secured by changing the capacity of the oscillating circuit, as by opening and closing a circuit through an auxiliary condenser 91 by means of a key 92.

For wireless telephony it is preferable to employ an arrangement such as is shown in Fig. 29, in which the working oscillating circuit is separate from the oscillating circuit which excites the field, as illustrated in Fig. 5. The inductance 24 of Fig. 5 is utilized as the primary of a step-up transformer, whose secondary is in the antenna-circuit. The tertiary of the transformer is closed by a carbon telephone-transmitter 90, having a sufficient current-carrying capacity to answer the purpose. Any of the arrangements which have been described for producing the oscillations may be employed for utilizing such oscillations in any of the ways shown in Figs. 26 to 29.

The arrangement in which a separate working circuit is used in shunt with the exciting-circuit is particularly effective in wireless signaling and especially in wireless telephony. The period of the exciting-circuit determines the frequency of the oscillations, while the natural period of the working circuit determines the intensity of its oscillations. The latter are free oscillations of large amplitude when the two circuits are in tune, and a small variation in the electrical constants of the circuit will cause the resulting forced oscillations to fall off greatly in amplitude. Thus the radiation may be controlled by cutting in or out inductance or capacity—an operation which in this arrangement involves a small expenditure of energy and hence no special precaution for handling a large current. Thus a simple key of small size or a carbon telephone-transmitter may be used effectively. A similar result may be obtained by varying the electrical constants of the exciting-circuit. A further advantage of this arrangement is in the fact that the intensity and frequency of the exciting-current is practically independent of the amount of energy that is being drawn from the apparatus. The apparatus thus works in much the same manner as a shunt-dynamo, taking energy from the source of power in proportion to the energy expended in the working circuit. Where it is desired to increase the excitation with increasing output, a compound field, such as is illustrated in Fig. 3, may be used. The working circuit is not necessarily a tuned circuit: for some purposes an aperiodic circuit may be substituted for the tuned working circuit.

This application is a division of my application, Serial No. 247,826, filed February 28, 1905, in which the method herein described is claimed.

What I claim is—

1. An apparatus for producing electrical oscillations, wherein are combined an elec-

trical oscillating circuit, a field excited or controlled by the oscillations of said electrical oscillating circuit and acting to electrically commutate energy, and means for adding by such commutation increments of energy to such oscillating circuit.

2. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a field excited or controlled by the oscillations of such circuit, a sensitive gap or gaps acted upon by such field to electrically commutate energy therein, and means for adding by such commutation increments of energy to such oscillating circuit.

3. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a magnetic field excited or controlled by the oscillations of such circuit and acting to electrically commutate energy, and means for adding by such commutation increments of energy to such oscillating circuit.

4. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a magnetic field excited or controlled by the oscillations of said circuit, a sensitive gap or gaps acted on by said magnetic field to electrically commutate energy therein, and means for adding by such commutation increments of energy to such oscillating circuit.

5. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a field excited or controlled by the oscillations of said circuit, a gaseous medium acted upon by said field to electrically commutate energy therein, and means for adding by such commutation increments of energy to such oscillating circuit.

6. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a field excited or controlled by the oscillations of said circuit, a rarefied gaseous medium acted upon by said field to electrically commutate energy therein, and means for adding by such commutation increments of energy to such oscillating circuit.

7. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a magnetic field excited or controlled by the oscillations of said circuit, a gaseous medium acted upon by said magnetic field to electrically commutate current therein, and means for adding by such commutation increments of energy to such oscillating circuit.

8. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a magnetic field excited or controlled by the oscillations of said circuit, a vapor tube or tubes acted upon by said magnetic field to electrically commutate current in such tube or tubes, and means for adding by such commutation increments of energy to such oscillating circuit.

9. An apparatus for producing electrical oscillations, wherein are combined a variable magnetic field, two or more alternative circuits the conductivity of one or more of which is periodically altered by the influence of such variable magnetic field thereby causing a periodic variation in the currents in said circuits, means for exciting oscillations of definite frequency by these variable currents, and means for controlling the variations of the magnetic field by such oscillations.

10. An apparatus for producing electrical oscillations, wherein are combined a variable magnetic field, two or more alternative circuits the conductivity of one or more of which is periodically altered by the influence of such variable magnetic field, thereby causing a periodic variation in the currents in said circuits, means for controlling the variation of such magnetic field by such currents, and a circuit or circuits operatively connected with the system and controlling by means of capacity and inductance the frequency of the variations in said currents.

11. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a sensitive medium through different paths in which an electric current passes, means for electrically commutating the current in such different paths, and means for adding by such commutation increments of energy to such oscillating circuit.

12. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a gaseous medium through different paths in which an electric current passes, means for electrically commutating the current in such different paths, and means for adding by such commutation increments of energy to such oscillating circuit.

13. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a plurality of similar paths or circuits, means for electrically commutating the energy in such similar paths or circuits in synchronism with the oscillations of the oscillating-circuit, and means for adding by such commutation increments of energy to the oscillating circuit.

14. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a plurality of similar paths or circuits, means for electrically commutating electrical currents in such similar paths or circuits, and means for adding by such commutation increments of energy to the oscillating circuit.

15. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, two similar parallel

circuits, means for electrically commutating electrical currents in said similar parallel circuits in synchronism with the oscillations of such oscillating circuit, and means for adding by such commutation increments of energy to the oscillating circuit.

16. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a sensitive medium through different paths in which an electric current passes, a magnetic field affecting the current in such paths in synchronism with the oscillations of such oscillating circuit, thereby electrically commutating said current, and means for adding by such commutation increments of energy to such oscillating circuit.

17. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a gaseous medium through different paths in which an electric current passes, a magnetic field affecting the current in such paths in synchronism with the oscillations of such oscillating circuit, thereby electrically commutating said current, and means for adding by such commutation increments of energy to such oscillating circuit.

18. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit a vapor tube or tubes through different paths in which an electric current passes, a magnetic field affecting the current in such paths in synchronism with the oscillations of such oscillating circuit, thereby electrically commutating said current, and means for adding by such commutation increments of energy to such oscillating circuit.

19. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a sensitive medium through different paths in which an electric current passes, an alternating magnetic field oppositely and alternately affecting the current in such paths to commutate the electric current in such medium, means for adding by such commutation increments of energy to such oscillating circuit, and means for controlling the alternating magnetic field by such oscillations.

20. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a gaseous medium through different paths in which an electric current passes, an alternating magnetic field oppositely and alternately affecting the current in such paths, thereby commutating said current, means for adding by such commutation increments of energy to such oscillating circuit, and means for controlling the alternating magnetic field by such oscillations.

21. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a vapor tube or tubes through different paths in which an electric current passes, an alternating magnetic field oppositely and alternately affecting the current in such paths, thereby commutating said current, means for adding by such commutation increments of energy to such oscillating circuit, and means for controlling the alternating magnetic field by such oscillations.

22. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, two channels in which a comparatively steady current is established connected with such circuit, a sensitive gap in each channel shunted by said circuit, and a magnetic field controlled by the oscillations in such circuit for producing opposite effects upon the current in the two gaps to divert current alternately from said channels through said oscillating circuit.

23. An apparatus for producing electrical oscillations, wherein are combined an oscillating circuit, two channels in which a comparatively steady current is established connected with such circuit, a sensitive gap in a gaseous medium included in each channel and shunted by said circuit, and a magnetic field controlled by the oscillations in such circuit for producing opposite effects upon the current in the two gaps to divert current alternately from said channels through said oscillating circuit.

24. An apparatus for producing electrical oscillations, wherein are combined an oscillating circuit, two or more alternative circuits through which an electric current passes, a sensitive gap or gaps in said alternative circuits, an alternating magnetic field whose flux is perpendicular to the current in said gap or gaps for periodically diverting the current therein, thereby electrically commutating the current in said circuits, means for adding by such commutation increments of energy to said oscillating circuit, and means for controlling the alternating magnetic field by such oscillations.

25. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, two alternative circuits through which an electric current passes, a sensitive gap in each of said alternative circuits, an alternating magnetic field whose flux is perpendicular to the flow of current through said gaps for diverting the current in said gaps alternately and oppositely, thereby electrically commutating the current in said circuits, means for adding by such commutation increments of energy to said electrical oscillating circuit, and means for controlling the alternating magnetic field by such oscillations.

26. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a sensitive medium

through two adjacent paths in which an electric current passes, an alternating magnetic field whose flux is perpendicular to the plane of said paths for diverting the current in said paths alternately and oppositely, thereby commutating the current in said paths, means for adding by such commutation increments of energy to said electrical oscillating circuit, and means for controlling the alternating magnetic field by such oscillations.

27. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a vapor-tube through two adjacent paths in which an electric current passes, said tube being provided with two anodes and a single cathode, an alternating magnetic field acting on said tube and whose flux is perpendicular to the plane of the electrodes of the tube for diverting the current in said paths alternately and oppositely, thereby electrically commutating the current between the two paths in the tube, means for adding by such commutation increments of energy to said electrical oscillating circuit, and means for controlling said alternating field by such oscillations.

28. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a magnetic field controlled thereby for commutating an electric current, a working circuit in parallel with the controlling oscillating circuit, and means for supplying to said working circuit the oscillations produced by said controlling oscillating circuit.

29. An apparatus for producing electrical oscillations, wherein are combined an electrical oscillating circuit, a magnetic field controlled thereby for commutating an electric current, a second or working oscillating circuit in parallel with and tuned to the same frequency as the controlling oscillating circuit, and means for supplying to said second or working oscillating circuit the oscillations produced by said controlling oscillating circuit.

30. An apparatus for producing electrical oscillations of variable intensity, wherein are combined an electrical oscillating circuit, a magnetic field controlled thereby for commutating an electric current, a second oscillating circuit, means for impressing such oscillations on said second oscillating circuit, and means for controlling the intensity of the oscillations by varying the electrical constants of one or both circuits.

31. An apparatus for producing electrical oscillations of variable intensity, wherein are combined a generator of sustained electrical oscillations, a resonant circuit, means for impressing such oscillations on said resonant circuit, and means for controlling the intensity of the oscillations in said circuit by throwing the circuit in and out of tune with the generator.

32. An apparatus for producing electrical oscillations of variable intensity, wherein are combined a generator of sustained electrical oscillations, a resonant circuit, means for impressing such oscillations on said resonant circuit, and means for controlling the intensity of the oscillations by varying the electrical constants of one or both parts of the system by shunting capacity or inductance.

33. An apparatus for producing electromagnetic waves, wherein are combined an electrical oscillating circuit, different paths in a sensitive medium through which paths an electric current passes, means for electrically commutating the current in said paths, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

34. An apparatus for producing electromagnetic waves, wherein are combined an electrical oscillating circuit, different paths in a gaseous medium through which an electric current passes, means for electrically commutating the current in such paths, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

35. An apparatus for producing electromagnetic waves, wherein are combined an oscillating circuit, a plurality of similar paths or circuits, means for electrically commutating energy in such similar paths or circuits in synchronism with the oscillations of such oscillating circuit, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

36. An apparatus for producing electromagnetic waves, wherein are combined an electrical oscillating circuit, a plurality of similar paths or circuits, means for electrically commutating electrical currents in such similar paths or circuits in synchronism with the oscillations of such oscillating circuit, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

37. An apparatus for producing electromagnetic waves, wherein are combined an electrical oscillating circuit, two similar parallel circuits, means for electrically commutating electrical currents in said parallel circuits in synchronism with the oscillations of such oscillating circuit, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

38. An apparatus for producing electro-

magnetic waves, wherein are combined an electrical oscillating circuit tuned to a high frequency, a field excited or controlled by the oscillations of said electrical oscillating circuit and acting to electrically commutate energy, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

39. An apparatus for producing electromagnetic waves, wherein are combined an electrical oscillating circuit tuned to a high frequency, a field excited or controlled by the oscillations of said circuit, a sensitive gap or gaps acted upon by said field to electrically commutate energy therein, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

40. An apparatus for producing electromagnetic waves, wherein are combined an electrical oscillating circuit tuned to a high frequency, a magnetic field excited or controlled by the oscillations of said circuit and acting upon an electric current to electrically commutate said current, means for adding by such commutation increments of energy to said electrical oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

41. An apparatus for producing electromagnetic waves, wherein are combined an electrical oscillating circuit tuned to a high frequency, a magnetic field excited or controlled by the oscillations of said circuit, a sensitive gap or gaps, the electric current in said gap or gaps being acted upon by said field to electrically commutate the energy in such gap or gaps, means for adding by such commutation increments of energy to said electrical oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

42. An apparatus for producing electromagnetic waves, wherein are combined an electrical oscillating circuit tuned to a high frequency, a magnetic field excited or controlled by the oscillations of said circuit, a gaseous medium, the electric current in such medium being acted upon by said field to electrically commutate said current, means for adding by such commutation increments of energy to said electrical oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

43. An apparatus for producing electromagnetic waves, wherein are combined an electrical oscillating circuit tuned to a high frequency, a magnetic field excited or controlled by the oscillations of said circuit, a vapor tube or tubes, the electric current in such tube or tubes being acted upon by said field to electrically commutate said current, means for adding by such commutation increments of energy to said electrical oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

44. An apparatus for producing electromagnetic waves, wherein are combined an oscillating circuit tuned to a high frequency, a sensitive medium through different paths in which an electric current passes, a magnetic field affecting the current in such paths in synchronism with the oscillations of such oscillating circuit to electrically commutate said current, means for adding by such commutation increments of energy to said oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said rediating circuit.

45. An apparatus for producing electromagnetic waves, wherein are combined an oscillating circuit tuned to a high frequency, a gaseous medium through different paths in which an electric current passes, a magnetic field affecting the current in such paths in synchronism with the oscillations of such oscillating circuit to electrically commutate said current, means for adding by such commutation increments of energy to said oscillating circuit, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

46. An apparatus for producing electromagnetic waves, wherein are combined an oscillating circuit tuned to a high frequency, a sensitive medium through different paths in which an electric current passes, an alternating magnetic field oppositely and alternately affecting the current in such paths to commutate the electric current in such medium, means for adding by such commutation increments of energy to said oscillating circuit, means for controlling the alternating magnetic field by such oscillations, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

47. An apparatus for producing electromagnetic waves, wherein are combined an oscillating circuit tuned to a high frequency, a gaseous medium through different paths in which an electric current passes, an alternating magnetic field oppositely and alternately affecting the current in such paths to electrically commutate said current, means for adding by such commutation increments of energy to said oscillating circuit, means for controlling the alternating magnetic field by such oscillations, a radiating circuit, and means for impressing such oscillations upon said radiating circuit.

48. An apparatus for the wireless transmission of intelligence, wherein are combined an electrical oscillating circuit, different paths in a sensitive medium through which an electric current passes, means for electrically commutating the current in such different

paths, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, means for impressing the oscillations upon said radiating circuit, and means for interrupting or varying the character or intensity of the radiations to convey intelligence.

49. An apparatus for the wireless transmission of intelligence, wherein are combined an electrical oscillating circuit, different paths in a gaseous medium through which an electric current passes, means for electrically commutating the current in such different paths, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, means for impressing the oscillations upon said radiating circuit, and means for interrupting or varying the character or intensity of the radiations to convey intelligence.

50. An apparatus for the wireless transmission of intelligence, wherein are combined an electrical oscillating circuit, a plurality of similar paths or circuits, means for electrically commutating energy in said similar paths or circuits in synchronism with the oscillations of such oscillating circuit, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, means for impressing such oscillations upon said radiating circuit, and means for interrupting or varying the character or intensity of the radiations to convey intelligence.

51. An apparatus for the wireless transmission of intelligence, wherein are combined an electrical oscillating circuit, a plurality of similar paths or circuits, means for electrically commutating electrical currents in said similar paths or circuits in synchronism with the oscillations of such oscillating circuit, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, means for impressing such oscillations upon said radiating circuit, and means for interrupting or varying the character or intensity of the radiations to convey intelligence.

52. An apparatus for the wireless transmission of intelligence, wherein are combined an electrical oscillating circuit, two similar parallel circuits, means for electrically commutating electrical currents in said similar parallel circuits in synchronism with the oscillations of such oscillating circuit, means for adding by such commutation increments of energy to such oscillating circuit, a radiating circuit, means for impressing such oscillations upon said radiating circuit, and means for interrupting or varying the character or intensity of the radiations to convey intelligence.

53. An apparatus for the wireless transmission of intelligence, wherein are combined an electrical oscillating circuit, a field excited or controlled by the oscillations of said circuit and acting to electrically commutate energy, means for adding by such commutation increments of energy to such electrical oscillating circuit, a radiating circuit, means for impressing the oscillations on said radiating circuit, and means for interrupting or varying the character or intensity of the radiations to convey intelligence.

54. An apparatus for the wireless transmission of intelligence, wherein are combined an electrical oscillating circuit, a magnetic field controlled thereby for commutating an electric current to produce electrical oscillations, a radiating circuit, means for impressing such oscillations upon said radiating circuit, and means for interrupting or varying the character or intensity of the radiations to convey intelligence.

55. An apparatus for the wireless transmission of intelligence, wherein are combined an electrical oscillating circuit, a magnetic field controlled thereby for commutating an electric current whereby sustained electrical oscillations are continuously generated, a radiating circuit, means for impressing such oscillations upon said radiating circuit, and means for interrupting or varying the character or intensity of the radiations to convey intelligence.

56. An apparatus for the wireless transmission of intelligence, wherein are combined an electrical oscillating circuit, a magnetic field controlled thereby for commutating an electric current whereby sustained electrical oscillations are continuously generated, a radiating circuit, means for impressing such oscillations upon said radiating circuit, and means for interrupting or varying the character or intensity of the radiations by varying the electrical constants of the system to convey intelligence.

57. An apparatus for the wireless transmission of intelligence, wherein are combined two oscillating circuits, a radiating circuit, means for impressing upon said radiating circuit the electrical oscillations set up in said oscillating circuits, means for controlling the frequency of the radiations by one oscillating circuit, and means for controlling the intensity of the radiations by varying the electrical constants of one or both oscillating circuits.

58. An apparatus for the wireless transmission of intelligence, wherein are combined two electrical oscillating circuits, a magnetic field for commutating an electric current whereby sustained electrical oscillations are continuously generated in said system of circuits, means for controlling the rate of commutation by the oscillations of one of the oscillating circuits, a radiating circuit, means for impressing the oscillations of the other oscillating circuit upon said radiating circuit,

and means for controlling the intensity of the radiations by varying the electrical constants of one or both oscillating circuits.

59. An apparatus for the wireless transmission of intelligence, wherein are combined a generator continuously generating sustained electrical oscillations, a resonant circuit, means for impressing such oscillations on said resonant circuit, means for exciting electromagnetic radiations by the oscillations in the resonant circuit, and means for controlling the intensity of the radiations by throwing the resonant circuit in and out of tune with the generator.

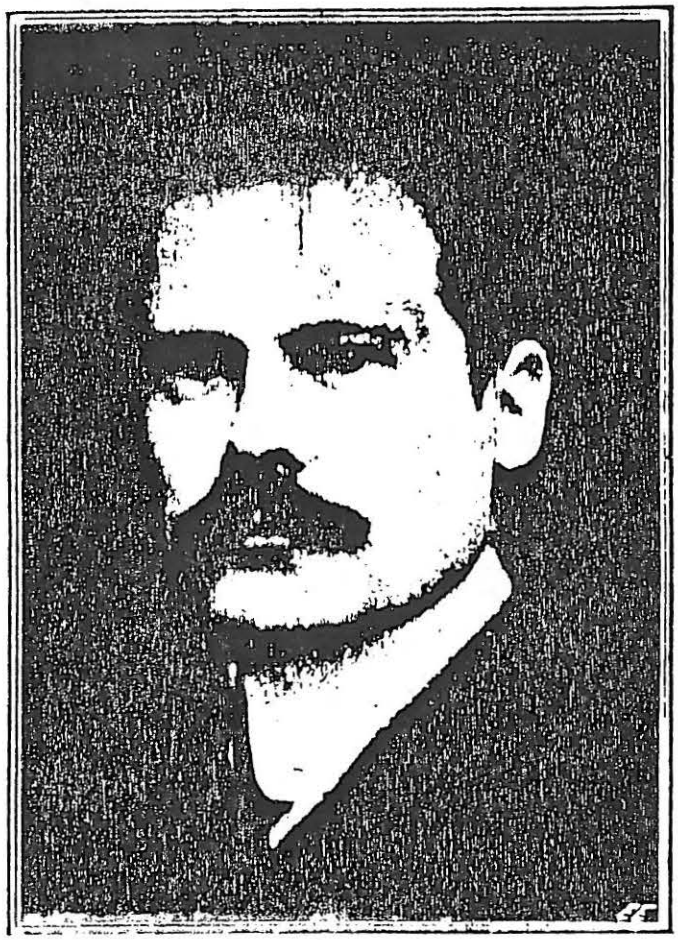
60. An apparatus for the wireless transmission of intelligence, wherein are combined a generator of sustained electrical oscillations, a resonant circuit, means for impressing such oscillations on said resonant circuit, means for exciting electromagnetic radiations by the oscillations in the resonant circuit, and means for controlling the intensity of the radiations by varying the relative frequency of the generator and the resonant circuit.

61. An apparatus for the wireless transmission of intelligence, wherein are combined a generator of sustained electrical oscillations, a resonant circuit, means for impressing such oscillations on said resonant circuit, means for exciting electromagnetic radiations by the oscillations in the resonant circuit, and means for controlling the intensity of the radiations by shunting capacity or inductance.

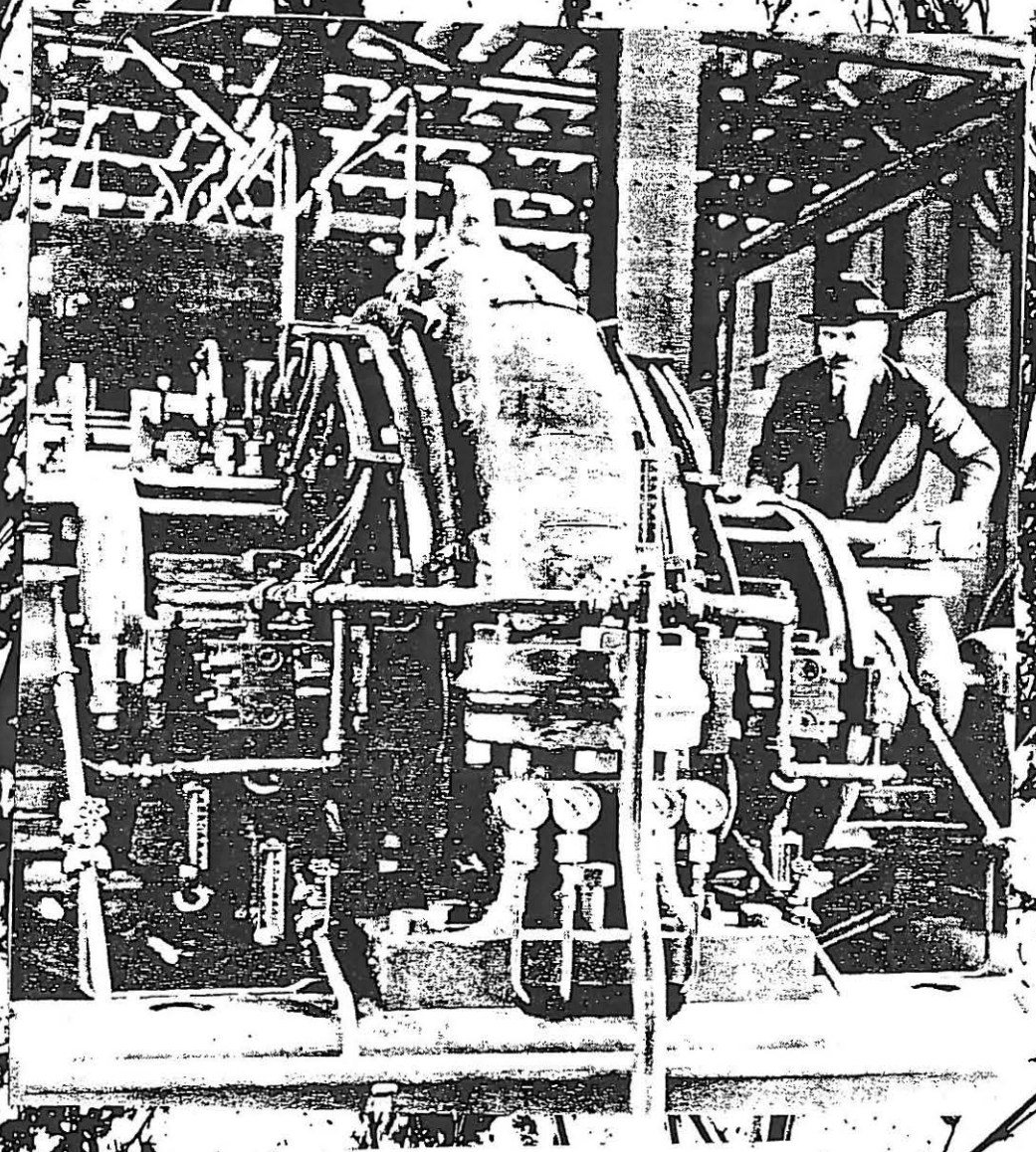
This specification signed and witnessed this 9th day of November, 1905.

FREDERICK K. VREELAND.

Witnesses:
AUG. LONG,
JOHN S. LOTSCH.



E. F. W Alexanderson, Well-known Radio and Electrical Engineer, Awarded the "I. R. E." Gold Medal.

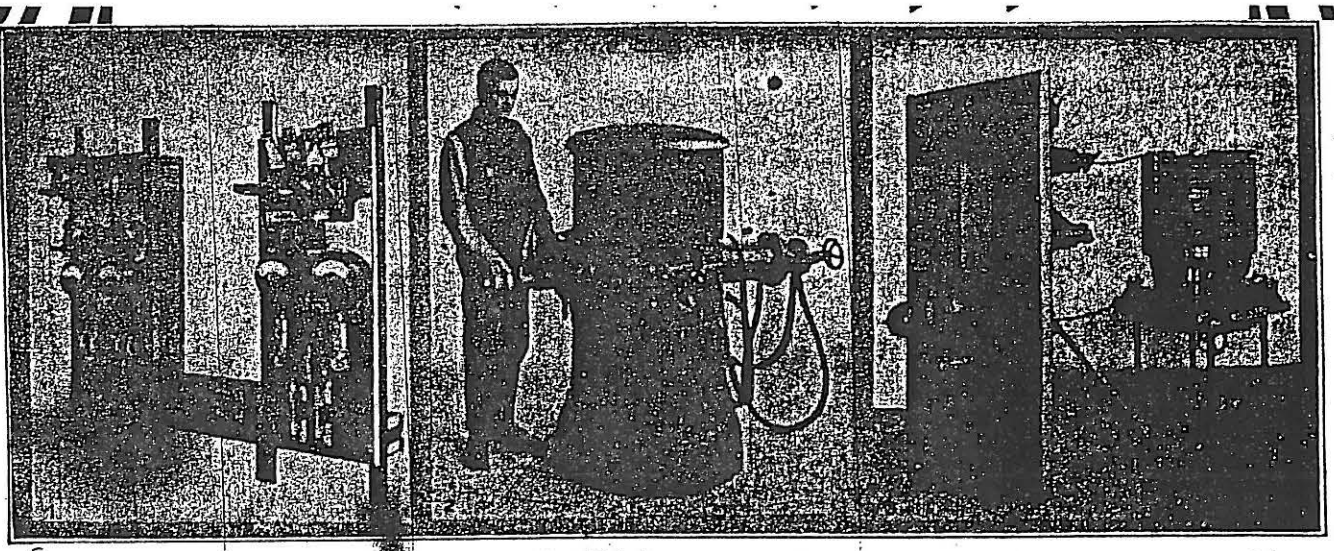




ERNST F. W. ALEXANDERSON



VALDEMAR POULSEN



The Above Photographs Show Some of the Remarkable High Power Radio Arc Telephone Transmitter Equipment, Developed by an American Concern During the War. Passing Beyond the Wireless Dreams of Even Valdemar Poulsen Himself, This Concern Has Developed Powerful Arc Transmitters for Both Wireless Telephony and Telegraphy in Various Sizes Up to 1,000 K.W. Rating. The Triple Panel Switch-board Here Shown, Was Built for Controlling a High Power Arc Transmitter and Served to Control the Circuits of the Motor-Generator, the Arc Converter and Auxiliary Apparatus. The Photo Showing the Man Standing by the Large Arc Transmitter Illustrates the Huge Size of a 30 K W. Arc. The Third Photo Shows an Oscillation Transformer Developed for Tuning the Antenna Circuit of Arc Transmitters. The Signaling Relays Are Also Shown In This Photograph.

High-Power Radio Arcs

WHEN Valdemar Poulsen invented his famous Oscillating Arc, which today bears his name, and which is capable of quickly and very efficiently developing radio frequency currents of undreamt of magnitudes, he probably never thought that arcs rated at several hundred kilowatts, and even up to a thousand kilowatts, would be built some day.

However, as the accompanying photographs show, some very remarkable radio frequency arc generators have been built by the concern exploiting the Poulsen patents in this country. This concern has developt the Poulsen arc into a reliable and highly efficient generator or rather converter of direct or alternating current into a radio frequency current suitable for exciting an antenna such as used in all radio stations for the application of either wireless telephone or undampt wireless telegraphic transmission.

At the present time, there are in use in this country and abroad arc transmitters of the following sizes, which are manufactured by the American concern: 5, 20, 60, 100, 200, 350, 500, and 1,000 kilowatts. These arc radio transmitters are rated according to the normal amount of direct current power supplied to the converter.

The photograph herewith of an arc converter with a man shown standing opposite it, is a 30 kilowatt radio transmitter of this type. It is used to change direct current into radio frequency current as aforementioned, and shore stations of moderate power and the larger naval stations are frequently equipt with arc converters of this size.

Another view of modern arc transmitting apparatus for radio stations, which shows a double deck control switchboard for arc radio transmitting. A motor-generator set is required for converting the alternating or low voltage direct current into direct current of a more suitable and high voltage, averaging 450 to 600 volts, which is best suited for the efficient operation of the arc converters. The three panel switchboard here shown, serves to control the circuits of the motor-generator, the arc converter and auxiliary apparatus.

The third photo shows an oscillation transformer of recent type developt for tuning the antenna circuits of arc transmitters. This switchboard and helix are known as a wave changer and antenna loading inductor, as well as signaling relay system for a 30 kilowatt arc radio transmitter. The modern high-power radio arc transmitter is a very efficient and noiseless piece of machinery. The efficiency of these arc transmitters is surprisingly high, about ⅔ to ¾ of the direct current power supplied to the arc being converted into radio frequency energy, in the antenna circuit. The arc flame is rated with a theoretical efficiency of 50%. These arcs much resemble the ordinary street arc lamp with which we are all familiar, but burn in a heavily enclosed chamber, filled with a gas containing hydrogen, and illuminating gas has been used very successfully in the arc chambers.

The two electrodes between which the arc proper is situated, is placed between the poles of two powerful electro-magnets, which produce a strong transverse magnetic field tending to blow the arc out. The negative electrode is usually composed of carbon or graphite, while the positive electrode is constructed of copper and arranged so as to be water cooled. Usually a small motor rotates the carbon electrode in these arcs, so as to cause the arc proper to burn evenly. This appartus has been so carefully and thoroly improved, that the only adjustment of the arc, is that occasionally required to adjust the length of the arc flame, until maximum antenna current is obtained.

With these large arcs and big electrodes the carbon poles are decomposed very slowly, thus making it possible to operate the arc converter for several hours at a time, with but few slight adjustments of the carbon feed mechanism now in use.

There are two forms of magnetic circuit used in the modern radio arc transmitter, the open and the closed type. Where a very strong magnetic field is necessary as in the large size arcs, the closed magnetic circuit is employed. For arc generators rated at 100 kilowatts or less, the open magnetic circuit is commonly utilized in practise, and this is the type used on the 30 kilowatt arc generator here illustrated.

The magnetic field is set up in the open magnetic circuit arc of this type, by two large field coils, situated one below and the other above, the arc chamber. In these latest type arcs, the usual choke coils used in arc circuits, are built as an integral part of this series winding, and help to energize the magnetic circuit.

In the small arcs rated at from 15 to 20 kilowatts, the field coils are wound with cotton covered magnet wire, in layers, with a series of vertical air ducts to properly ventilate the windings and properly carry off the heat from them.

The arcs rated from 30 to 100 kilowatts have magnetizing field windings, formed of a number of pancake coils wound with copper strip, with micanite insulation, placed between turns. The pancake coils are then separated from one another by means of Bakelite spacers, and the coils are provided with both vertical and horizontal air ducts.

The radio experimenter will find the subject of oscillating arcs of extreme interest for the purpose of producing high frequency oscillations for wireless telegraph and telephony transmission. There are also many other wonderful phenomena which are produced by the tuned oscillating arc of Poulsen. One of the most interesting phases of this subject is the "speaking" arc, and in fact, this was one of the first fundamental experiments and facts on which the use of the arc for wireless telephony and telegraphy was developed. The "speaking arc" comprises the usual arc, preferably of the hand-fed type for experimental work, shunted by a large capacity and inductance. Suitable choke coils are placed in the D. C. supply circuit, one choke in each line and the voice currents are superimposed on the arc by means of a microphone and a telephone induction coil or small spark coil. The microphone is connected with several batteries, in series with the primary of this coil, and the secondary is sometimes shunted across the arc with a condenser in series.

As aforementioned, illuminating gas is used in the arc chamber when available, and alcohol is the hydro-carbon used frequently in the small size arc transmitters. Kerosene or coil oil are often used for high powered, short-wave arcs.—*Photos courtesy Federal Telegraph Company.*

Arc Telephony

The invention of wireless telephony is ascribed to Dr. Poulsen, who, in producing a practical generator of continuous waves, provided the essential " carrier " by which the actual forms of speech can be communicated by wireless. Using the Arc, wireless telephony was successfully transmitted over distances of several hundred miles in 1910. It was in connection with these transmissions that the first " broadcasting " was done. At that time the problem of impressing upon the aerial current variations corresponding to speech was exceedingly difficult, and large numbers of special microphones were employed. Later on improved methods became available in the magnetic amplifier and the three-electrode valve.

When using the Arc for telephony, purity of wave is much more essential than in telegraphy. Most of the Arc stations now in use have the Arc connected, for reasons of space and economy, directly in the aerial circuit, with the result that every slight disturbance in the Arc communicates to the aerial an irregularity which would make good telephony impossible. By reverting to coupled circuits and using valve modulation, successful telephony transmission can be given.

Experimental Work with the Arc

The cost of Arc apparatus being greater than that of most laboratory equipment, there has been much less experimental work done with the Arc than with the valve. Considering that in a device so obviously suited to the production of high-frequency currents there must be scope for further improvements and invention, this is to be regretted.

Poulsen Arcs have been installed at several of the London colleges, and at East London College circuits exist for the production of any

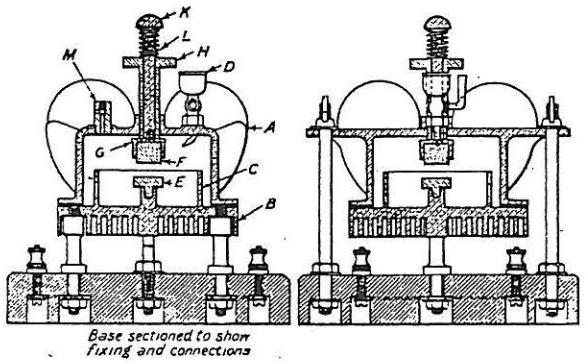


Fig. 8. A cross section through an experimental arc.

frequency from 1,000 to 100,000 periods per second.

Arcs capable of handling only a few watts will operate satisfactorily on suitable circuits when constructed on the lines of Fig. 8, *i.e.*, without an impressed magnetic field. Although obviously limited in scope such Arcs are exceedingly instructive, and allow a certain amount of experimental work to be done at a small cost. The small Arc of Fig. 8 will deliver 40 watts of high-frequency energy when connected to D.C. supply mains of 100/220 volts.

THE POULSEN SELECTIVE SYSTEM OF WIRELESS TELEGRAPHY.

BY A. FREDERICK COLLINS.

A new system of wireless telegraphy that gives considerable promise of solving the extremely difficult problem of selectivity, i. e., the transmission and reception of a number of messages in the same field of force simultaneously and without interference, has been devised and tried out by Valdemar Poulsen, the well-known inventor of the telegraphone.

The arrangement by which Poulsen hopes to accomplish the paramount result that is summed up in the word selectivity consists essentially of a new type of generator for producing continuous electrical oscillations. This generator will be subsequently described in detail, and the advantage of such high frequency currents over those having a periodic character that have hitherto been employed will also be pointed out.

Ever since 1897, when Sir Oliver Lodge applied to wireless telegraph transmitters and receptors the combination of open and closed circuits, and introduced the methods of tuning the circuits at either station individually and syntonizing them collectively, have persistent efforts been made by physicists and others to secure a suitable degree of resonance by providing the proper values of inductance, capacity, and resistance, and when these conditions prevailed, it was concluded the receiving resonator system would respond to a specific radiating oscillator system and to this one only. It is a matter of common knowledge that these tuning effects have been brought to a highly perfected state, thanks to the development of instruments which enable the operator easily to determine the inductance and capacity values, the frequency of the oscillations and the length of the emitted waves to be measured. It is likewise well known that syntonization as it has been practised has not fulfilled the requirements of selectivity in its commercial aspects, although it works out admirably from a theoretical viewpoint.

Nevertheless, these tuned and syntonized systems have served their purpose in extending the signaling distance as well as in reducing the initial energy; but the fact that the oscillations set up were periodic, and that between each succeeding train of oscillations a long interval of time elapses—that is, long compared with the time required for the oscillations to surge through the system before they are damped out into the form of electric waves—has militated against their usefulness as a means to the end of securing selectivity.

Believing that continuous oscillations would remedy this inherent defect Poulsen employs for the purpose the musical arc, whose phenomena were discovered by Duddell in 1900. The apparatus for producing the arc consists of an arc light, fed by a direct current, around which is shunted a condenser in series with an inductance coil as shown in Fig. 2, in which *A* is a choking coil, *B* the inductance coil, *C* the condenser in the shunt circuit, *D* a regulating resistance inserted in the direct-current circuit, and *X* the arc light. Now when certain conditions are satisfied the arc will give out a musical note and at the same time it will transform a portion of the direct current into an alternating current the amplitude of which is constant; and the energy dissipated in the condenser circuit in the form of ohmic losses is supplied by the direct current.



VALDEMAR POULSEN.

Duddell ascertained, however, that the arc light will emit a musical note only when there is a small change in the potential difference between the electrodes of the arc, and when the corresponding change in the current through the arc is numerically greater than the resistance in the condenser, and numerically less than the resistance of the direct-current circuit in series with the arc. These conditions are fulfilled if the arc is formed between solid carbons. This is an exceedingly simple method of producing not only high-frequency currents but also a very easy way of setting up continuous electric oscillations.

When experimenting some years ago with the musical arc, Poulsen made an observation which he followed up by occasional experiments, and which finally led him to the construction of a generator for producing continuous electric oscillations. In his first apparatus the carbons were placed horizontally and co-axially, as shown in Fig. 4, thus permitting an ordinary alcohol lamp to be held under the arc in such a manner that the latter and adjacent parts of the electrodes were surrounded by the vapor from the alcohol. An ordinary ammeter, *A*, was placed in the direct current circuit, and the hot-wire ammeter, *B*, for measuring high-frequency alternating currents, was placed in the condenser circuit. The direct current was taken from a 220-volt lighting circuit. constant amplitude were obtained, and these currents were further reinforced by blowing the arc out to a greater length with an electro-magnet, thus increasing its resistance. This is what the inventor terms a hydrogenic arc, and when its image was projected upon a screen with the condenser circuit broken, the arc was observed as a greenish blue spot having a faint core of a purple tint. When the arc was made musical

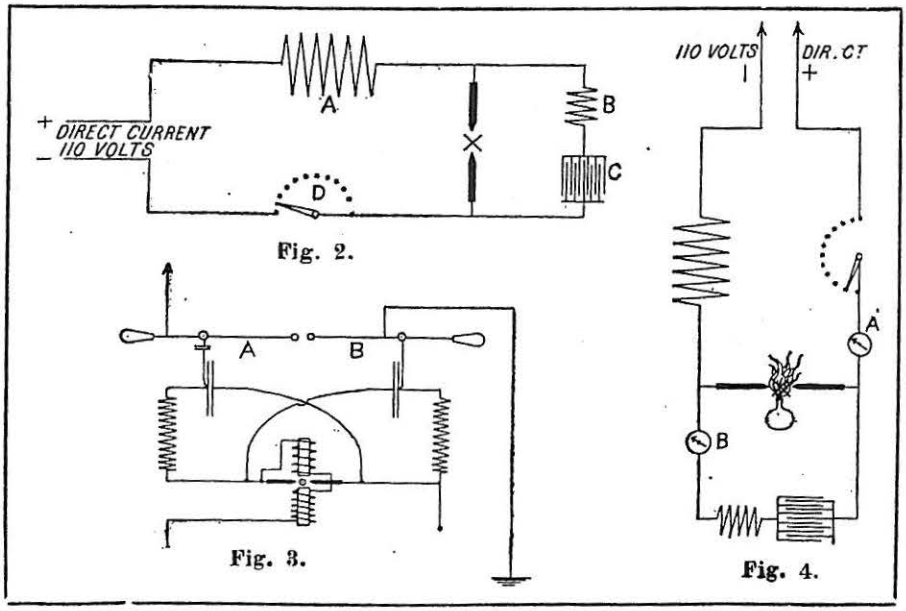


Fig. 2.

Fig. 3.

Fig. 4.

POULSEN'S SELECTIVE SYSTEM OF WIRELESS TELEGRAPHY.

by closing the condenser circuit, the colored spot became deeper and the purple core was very much more marked. This hydrogenic arc gave out musical notes, or rather electrical notes, the inventor tells us, of several hundred thousand oscillations per second, but it is possible to obtain some millions of oscillations per second. The excellent resonant effects that can be obtained with these oscillations indicate their continuity, and in a rotating mirror it will be seen that the oscillations are actually continuous.

With currents of high frequency spirits did not give as good results as hydrogen, nitrogen, coal gas, or ether. Again, it was shown to be necessary to draw the arc out to a certain length in order to start the oscillations, but when these have been started the length of the arc can generally be cut down a trifle without causing them to cease. If the length of the arc is increased, then the oscillations will continue, and will cease only when the distance between the electrodes has become so great that the arc is extinguished.

In some of his experiments Poulsen obtained in the condenser circuit—that is, the circuit in which the oscillations are set up—energy equivalent to about 1,560 watts (a little over 2 horse-power) the arc at the same time taking from the direct circuit about 3,170 watts, the efficiency thus being about 50 per cent. In these tests no effort was made to obtain the greatest efficiency or effect, the arc being placed in a water-cooled vessel without an outlet for the gas, this arrangement being necessary to determine the amount of energy consumed and transformed. It also lessened the intensity of the oscillations, since the composition of the gas was altered.

The Poulsen system of producing continuous electric oscillations is capable of taking care of a considerable amount of energy even when very high frequencies are used, as has been repeatedly proven by different experiments in connection with the ordinary lighting circuit of 220 volts. For instance, a resonating coil gave, when inserted in a properly balanced oscillating circuit, a noiseless, warm flame having a length of 12 centimeters; and if the flame is made short, it can be easily observed to be continuously oscillating, by means of a rotating mirror.

Another test was made by placing a large X-ray tube between the coils inductively coupled with an oscillation circuit, and in a short time the cathode and anti-cathode melted. Again, an ordinary 200-volt incandescent lamp glowed when placed in series with two persons, one of whom was connected with the oscillating circuit. Further, if the secondary coil of an ordinary induction coil is surrounded by a helix of thick copper wire, and the terminals are connected in series with a capacity of some microfarads capacity, the shunting in of the nitrogenic arc will produce a very loud singing flame 10 or 12 centimeters in length or more, and finally, an X-ray tube with this arrangement gives a very strong radiation.

From the foregoing it is obvious that such continuous electric oscillations are eminently adapted to the production and propagation of electric waves for wireless telegraphy, and that by properly proportioning the radiating aerial and receiving antenna the desired wave length can be emitted and utilized to produce a continuous resonance effect. The diagram, Fig. 3, shows two oscillating circuits tuned to the same frequency, and by means of which oscillating flames of about double the voltage can be obtained. To provide a wireless telegraph transmitter, it is necessary only to connect the radiating aerial wire with one side of the spark-gap *A* and the earthed terminal to the opposite side of the gap *B*.

The receptor may have any type of detector, although the magnetic detector is exceptionally well adapted for selective signaling in connection with the Poulsen hydrogenic arc emitter, the latter being shown in the illustration, Fig. 1. It is stated on good authority that a dozen messages have been transmitted and received between as many experimental sets by means of this new selective system without interference, and if this extraordinary result can be duplicated over distances of 50 or 100 miles, as the experiments thus far made between the inventor's two Danish stations indicate, an advance will have been made that, in its importance, will be second only to the introduction of wireless telegraphy itself.

cuit. Now, when the arc light was placed in the spirit vapor as cited above, a musical note was emitted, the pitch of which diminished. At the same time the hot-wire ammeter indicated a considerable increase in the oscillating current, while the direct current decreased in value. The result was further accentuated by the arc light's glowing less brightly. In succeeding experiments hydrogen and hydrogen com-

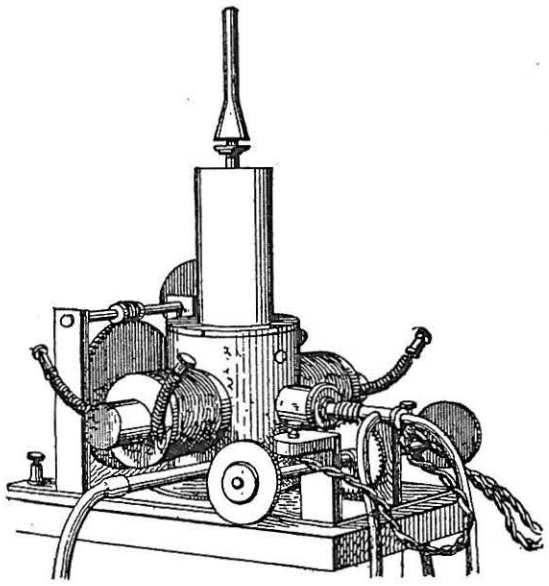


Fig. 1.—Poulsen Hydrogenic Arc Emitter.

pounds were used with approximately similar results, the length of arc required to give a maximum current in the condenser circuit being different than it was in those cases in which the arc was formed in air.

When copper and charcoal were employed as the electrodes, and a nitrogen compound was drawn through the walls of the carbon into the arc, where it was vaporized, the strongest continuous oscillations of



DR VALDEMAR POULSEN [*Frontispiece*

THE POULSEN ARC GENERATOR

BY

C. F. ELWELL, B.A., E.E. (STANFORD)

MEMBER INSTITUTION ELECTRICAL ENGINEERS
MEMBER AMERICAN INSTITUTE ELECTRICAL ENGINEERS
MEMBER ITALIAN INSTITUTE ELECTRICAL ENGINEERS
FELLOW INSTITUTE RADIO ENGINEERS
FORMERLY CHIEF ENGINEER POULSEN WIRELESS TELEGRAPH AND TELEPHONE COMPANY, FEDERAL TELEGRAPH COMPANY
UNIVERSAL RADIO SYNDICATE
MANAGING DIRECTOR C. F. ELWELL, LTD.

WITH 150 ILLUSTRATIONS

LONDON: ERNEST BENN LIMITED
8 BOUVERIE STREET, E.C.4
1923

Fig. 51 shows a 5 kw. arc converter, which is novel in that the magnetic circuit is of the " open " type. There is no return yoke, and the magnetic flux has a return path through the air. There is a large iron counterpoise and a large bedplate, and these serve to guide the return flux.

The chamber is quite narrow and is provided with a door to aid in the operation of cleaning the soot out of the chamber.

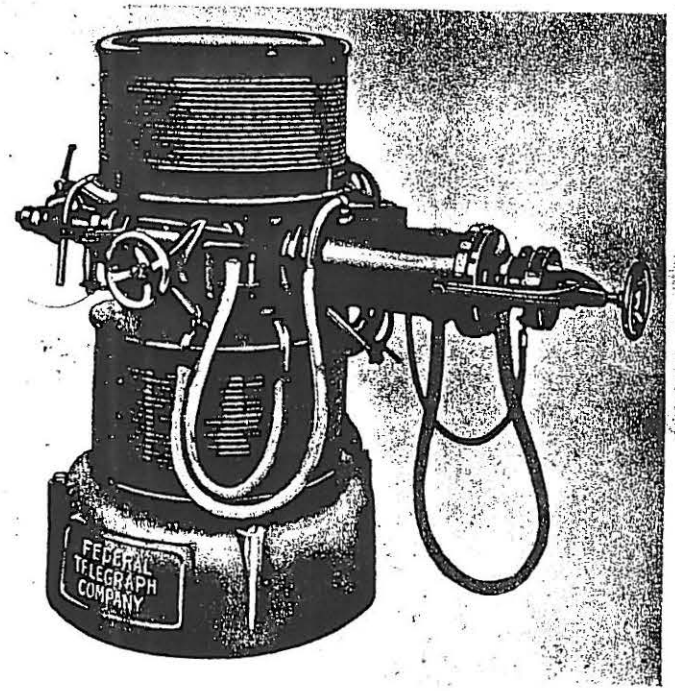


Fig. 52.—20 kw. Federal-Poulsen Arc Generator.

As this arc converter is for use with the Ignition Key method of signalling, the anode is made from a copper bar milled down to a narrow rectangular cross section brazed to a brass base. The renewable copper tip is provided with two small projections, one on either side, which serve as contact points and act as one of the electrodes of the Ignition Key signalling system.

The anode insulator is of ebony asbestos, which is protected from the direct heat and soot of the arc by means of a rubber gasket.

The exhaust receiver consists of a series of radiator coils clamped on the rear side. These coils provide a space into which the gas from the chamber may pulsate in pressure. They also act as a gas trap and prevent air leaking back into the chamber. This arc converter is equipped for operation with either alcohol or kerosene, or both, and the magnetically

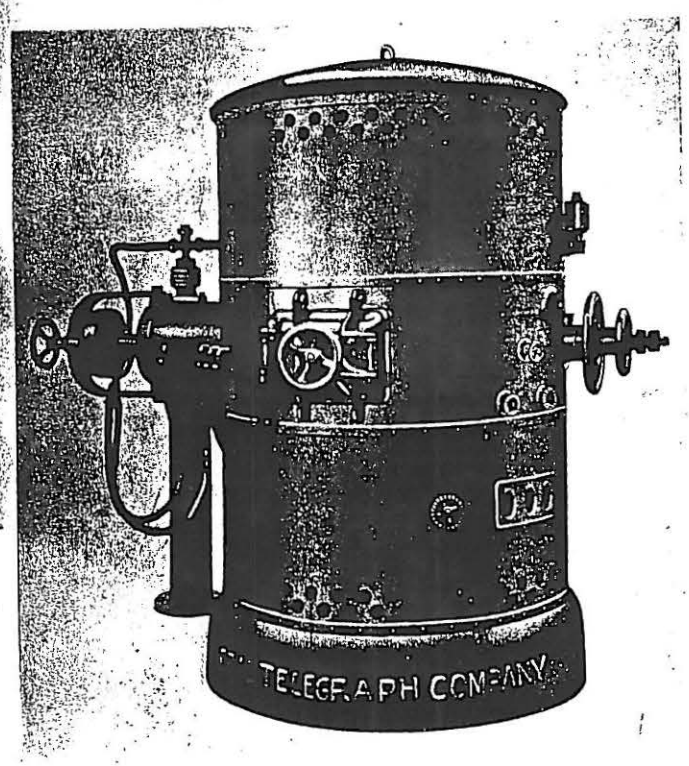


Fig. 53.—100 kw. Federal-Poulsen Arc Generator.

operated liquid hydrocarbon supply valves can be seen mounted on top of the motor rotating the carbon.

Fig. 52 shows a 20 kw. Federal-Poulsen arc converter, which is similar to the 5 kw. converter in that it is of the type with open magnetic circuit. The anode is fitted so that the arc may be struck and its length adjusted by moving this electrode. On account of the heat from an arc carrying as much as 20 kw., the ebony asbestos anode insulator has been removed to a

aerial circuit, and after a fraction of a second, the exact time being controllable by suitably adjusting the contacts, opens the dummy aerial circuit. Both circuits are therefore connected to the arc at the same time for a small fraction of a

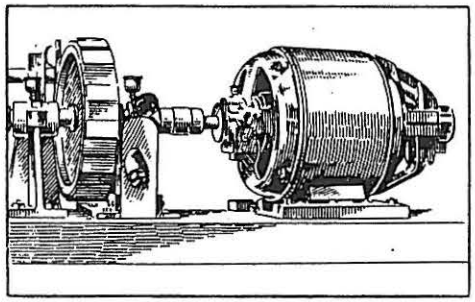


Fig. 91.—Federal Telegraph Co. Chopper.

second. The auxiliary contact seen in the switch is used in order to insert an economy resistance lamp in series with the solenoid when the latter is fully energized.

The photograph shows a complete key and also the following spare parts :

(*a*) Phosphor-bronze spring contact finger complete with copper tip.
(*b*) Renewable copper tip.
(*c*) Main contact—consisting of a copper disc.
(*d*) Moving system complete.
(*e*) Operating solenoid.

Fig. 91 shows one type of " chopper " interrupter as made by the Federal Telegraph Co. It consists of bronze wheels with alternating insulated and conducting segments. The note depends upon the number of segments in the circumference of the wheel, and its speed.

CHAPTER X

AUXILIARY APPARATUS

In order to employ the Poulsen arc generator in radio-telegraphy and telephony, other apparatus is necessary.

(1) Direct Current Supply Apparatus.
(2) High Frequency Apparatus.

A brief description of some of the more important pieces will now be given.

(1) Direct Current Supply Apparatus

(*a*) CHOKE COILS

In order to prevent the difference of H.F. potential present

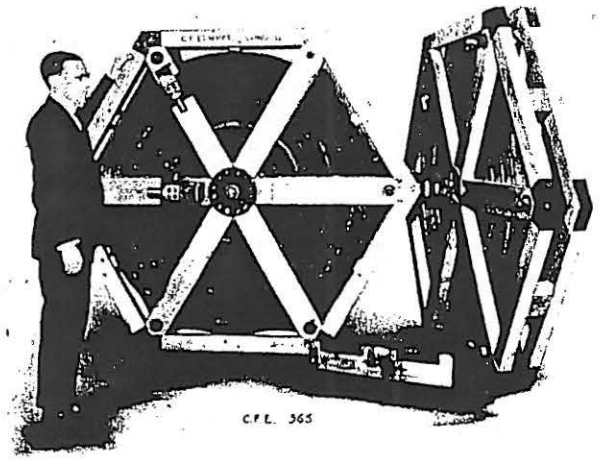


Fig. 92.—Choke Coils for 250 kw. Elwell-Poulsen Arc Generator.

between the anode and cathode of the Poulsen arc generator from causing H.F. current to flow through the d.c. supply mains to the dynamo, where it would be destructive of insulation and impair commutation, choke coils with large inductance,

MARCONI CO.

The Marconi Co. have constructed several Poulsen arc generators, of which Fig. 73 is an example of a machine rated at 25 kw.

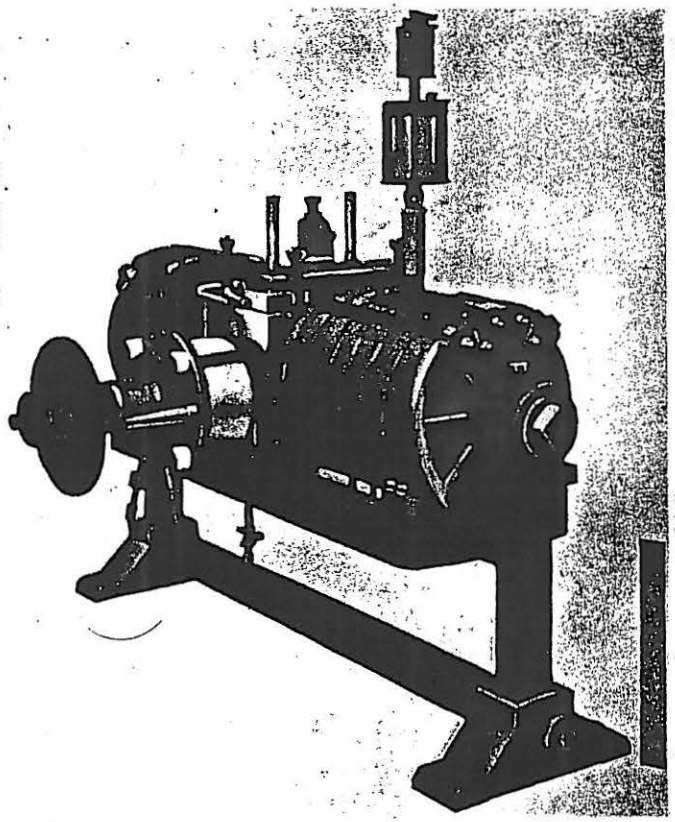


FIG. 73.—25 kw. Marconi-Poulsen Arc Generator.

DUTCH[82] CONSTRUCTION

Dr de Groot, of the Dutch East Indian Postal, Telegraphic and Telephonic Service, has undertaken to design and build what will be the largest Poulsen arc generator in existence, for the purpose of obtaining direct communication between the Dutch colonies and Holland.

The machine, which is being built in the Colony, is rated as 2400 to 3600 kw. (input). It will contain 260 tons of cast and sheet iron, no part of which must exceed 6 tons in weight in

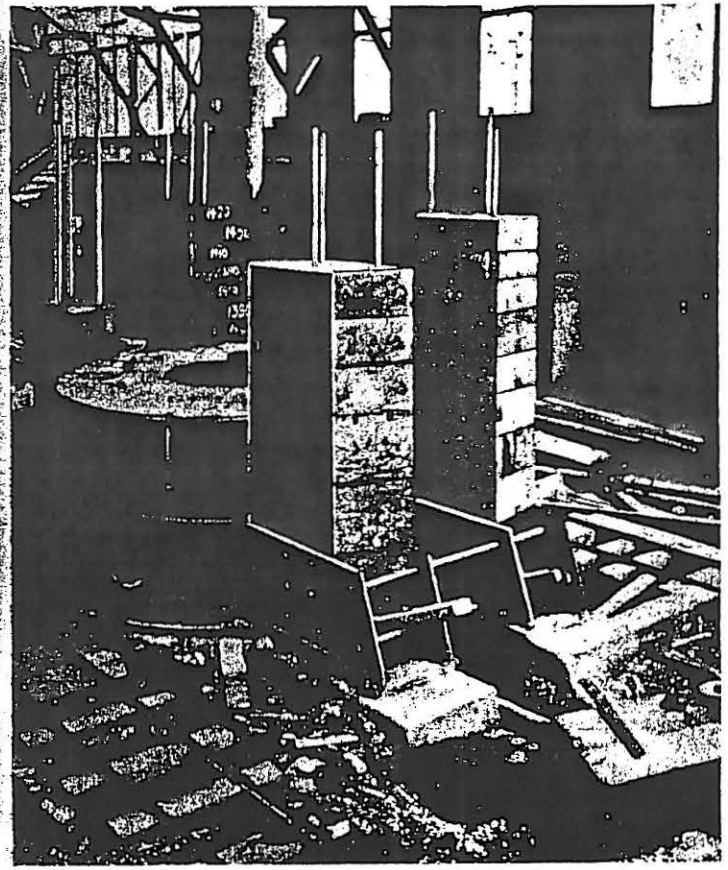


FIG. 74.—Field Coil and Magnetic Circuit of 2400-3600 kw. de Groot-Poulsen Arc Generator (by courtesy of *Radio Review*).

view of the uphill transport. The field coil will take 20 tons of copper, and the chamber will weigh nearly 6 tons. Special hydrogen generators will be installed. Fig. 74 shows the field coil and magnetic circuit in course of erection.

with 200 kw. machines. Fig. 66 shows the interior of the Abu Zabal [97], near Cairo, Station of the Imperial Wireless

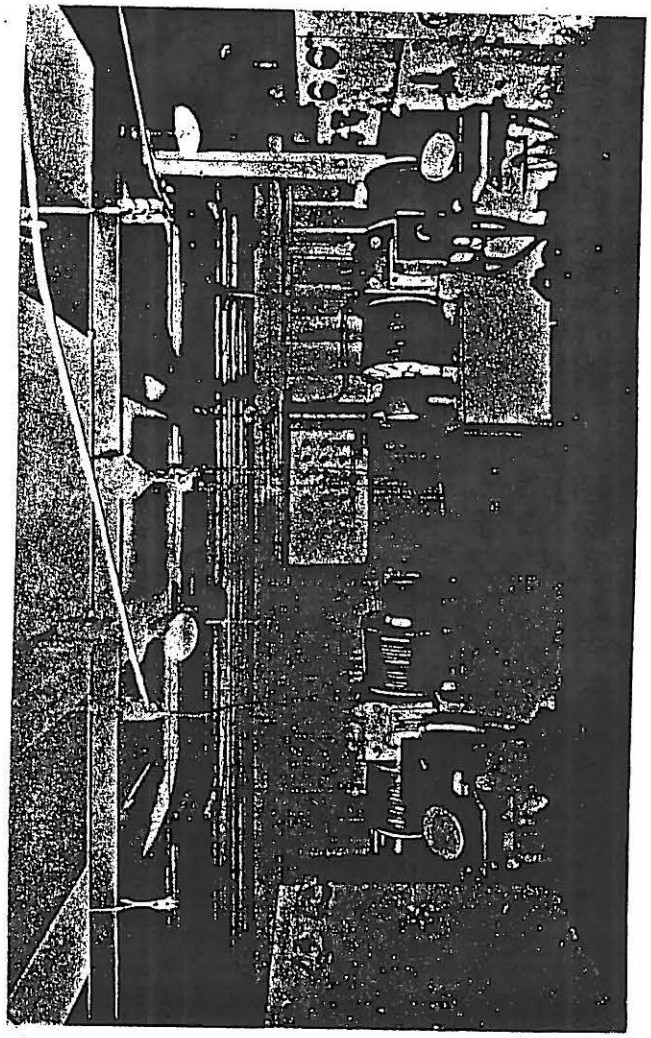


Fig. 64.—100–150 kw. Elwell-Poulsen Arc Generator at Eiffel Tower, France.

Chain. These machines are rated at 300 H.F. amperes (250-300 kw. input), and the field coils are oil cooled. Fig. 67 shows the interior of the Lyons [29, 81] Station with 350 kw. machines installed in duplicate. A later model of 350 kw. machine is shown in Fig. 68.

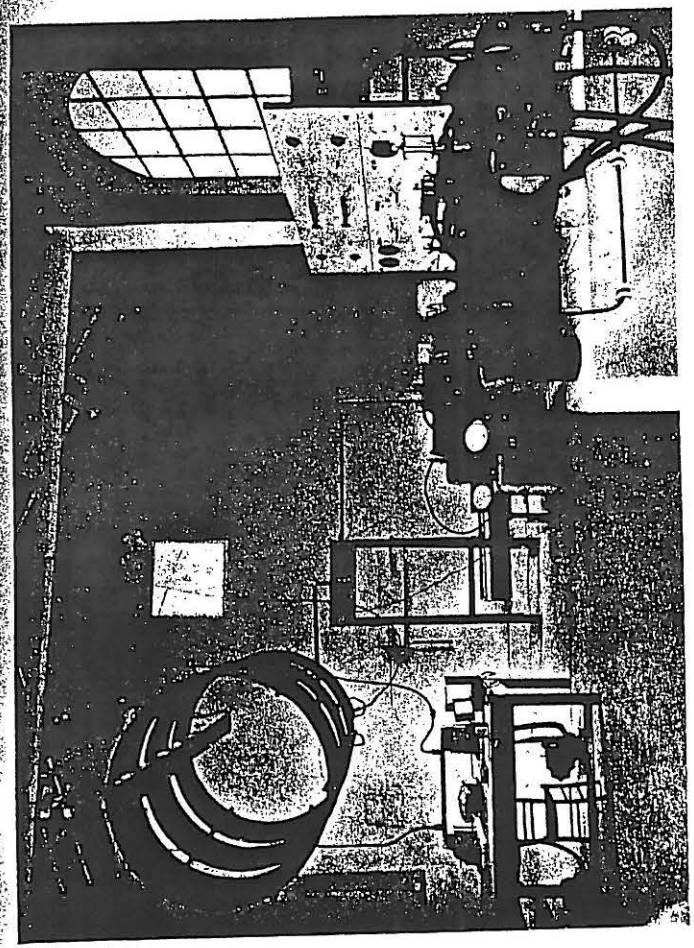


Fig. 65.—Interior of Rome, Italy Station, showing 200 kw. Elwell-Poulsen Arc Transmitter.

ADMIRALTY

The British Admiralty were very large users of Poulsen arcs during the war. In order to meet their own particular problems special designs were developed by the Signal School at Portsmouth.

The principal features of their designs were as follows :

considerable distance, by means of the water-cooled tubular projection from the chamber.

Fig. 53 shows a 100 kw. Federal-Poulsen arc converter which is substantially as the 20 kw. converter described above, except that the coils, etc., have been cased-in with sheet metal.

Fig. 54 shows a 500 kw. Federal-Poulsen arc converter. The magnetic circuit is extremely massive, weighing about 60 tons. The excitation is by means of one coil in a steel tank, which can be seen below the arc chamber. The anode is not used as the adjustable electrode on account of the high potentials used.

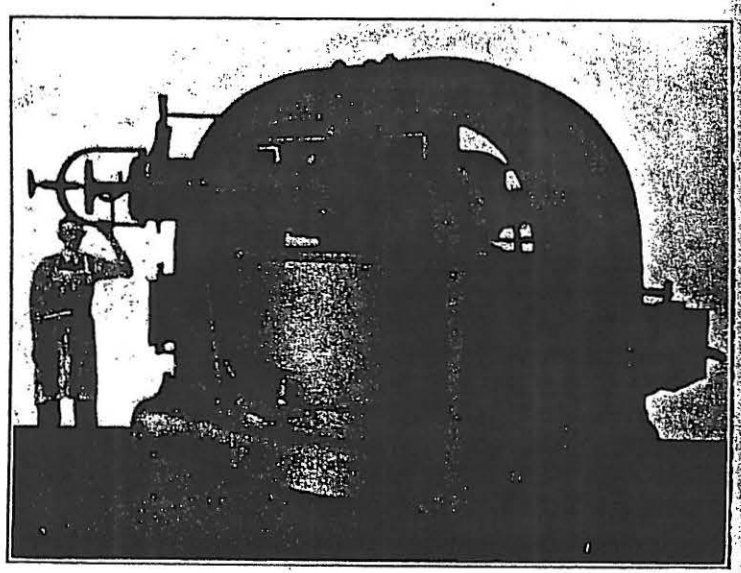


Fig. 54.—500 kw. Federal-Poulsen Arc Generator.

The handwheels are for the purpose of clamping the carbon tightly in its holder and adjusting the arc length.

Fig. 55 shows a 5 kw. Poulsen arc transmitter as developed by the Liberty Electric Corporation [53], and installed at the New York Radio Station, Babylon, N.Y.

ENGLISH [24] CONSTRUCTION

The earliest forms of Poulsen arc generators employed in England were of Danish and German design, and have already been described and illustrated.

The designs for which the author has been responsible follow the main lines of Danish design in the smaller machines, but differ in details.

Fig. 126 shows a laboratory type of Poulsen arc generator, which does not employ a magnetic field as greater constancy can be obtained without it. This type of arc will work on

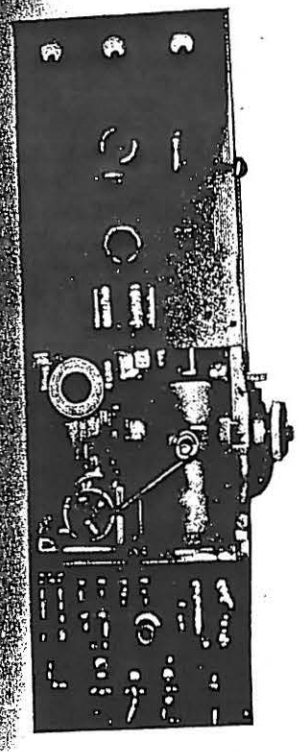


Fig. 55.—5 kw. Liberty-Poulsen Arc Transmitter.

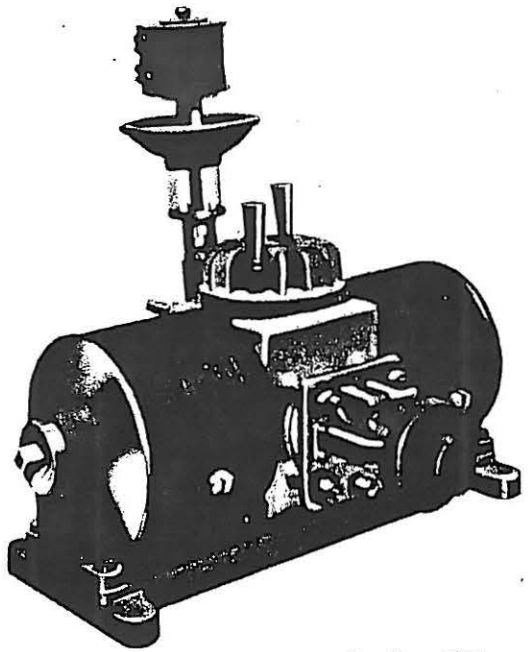


Fig. 56.—2 kw. Elwell-Poulsen Arc Generator.

110 to 220 volts d.c., and will furnish about 2 amperes of H.F. current. Chapter XII is devoted to some of the applications of this small Poulsen arc generator.

Fig. 56 shows an Elwell-Poulsen arc generator for use in installations requiring from 3 to 7 H.F. amperes (2 kw.). The chamber and anode are water cooled.

Fig. 57 shows an Elwell-Poulsen arc generator for from 8 to 15 H.F. amperes (3-7 kw. inputs). In order to give an idea of

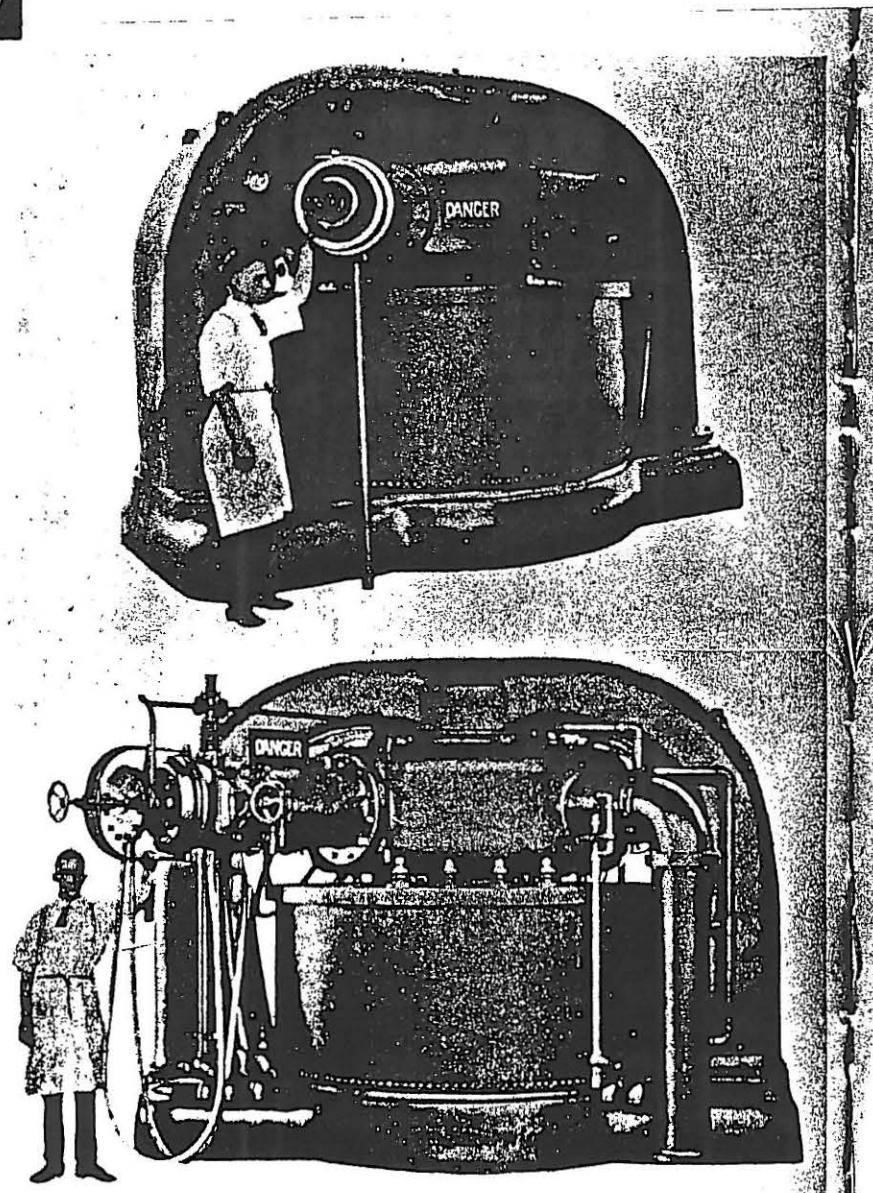


Fig. 144.—1000 kw. Federal-Poulsen Arc Generators at Bordeaux Station (by courtesy of *Radio Review*).

chamber and the field coil cooling oil is pumped into an octagonal cooling pond.

ARC GENERATOR AUXILIARY APPARATUS

A control cabinet is fitted with drum type controllers which successively open (1) valve for cooling water circulation, (2) valves controlling admission of alcohol and kerosene to the chamber for the purpose of forming the hydrogenous vapour, (3) start motor for the rotation of the carbon cathode, (4) close 1250 volt contactors (5) to (8) and short circuit the series resistances in series with the arc. A d.c. ammeter and voltmeter and a high frequency ammeter are also installed on the control cabinet.

A series resistance in four sections, each controlled by means of a contactor, is connected between the cathode and the earth.

A five-pole switch controls which arc converter is to be employed, while a two-way switch controls the high frequency supply to the aerial inductance.

A four-pole switch controls the supply of auxiliary current to the field coils. These switches are mounted upon a panel located between the two arc converters.

An electrically controlled security for assuring that the circulating water is flowing is also installed.

All oil and water piping is interconnected by means of valves in order that it may serve either arc converter.

HIGH FREQUENCY APPARATUS

The aerial sending inductance, which is in a special hexagonally shaped room, consists of about twenty-five turns of very finely subdivided cable mounted upon twelve vertical columns of porcelain insulators. The whole winding is installed inside a Faraday cage in order to protect the building from the effects due to the intense field. The inductance of the whole winding is approximately 3000 microhenries, which gives the station a maximum sending wave-length of 28,400 metres; with only a portion of the sending inductance in circuit the wave-length can be reduced to 13,000 metres.

A wave-changing switch is connected permanently to a number of points on the sending inductance. A movable arm controls the insertion of a number of turns more or less of the sending inductance in series with the aerial.

The keying system, on account of the large short circuit current to be handled, with upwards of 500 amperes in the aerial inductance, consists of seventy-eight relay contactors,

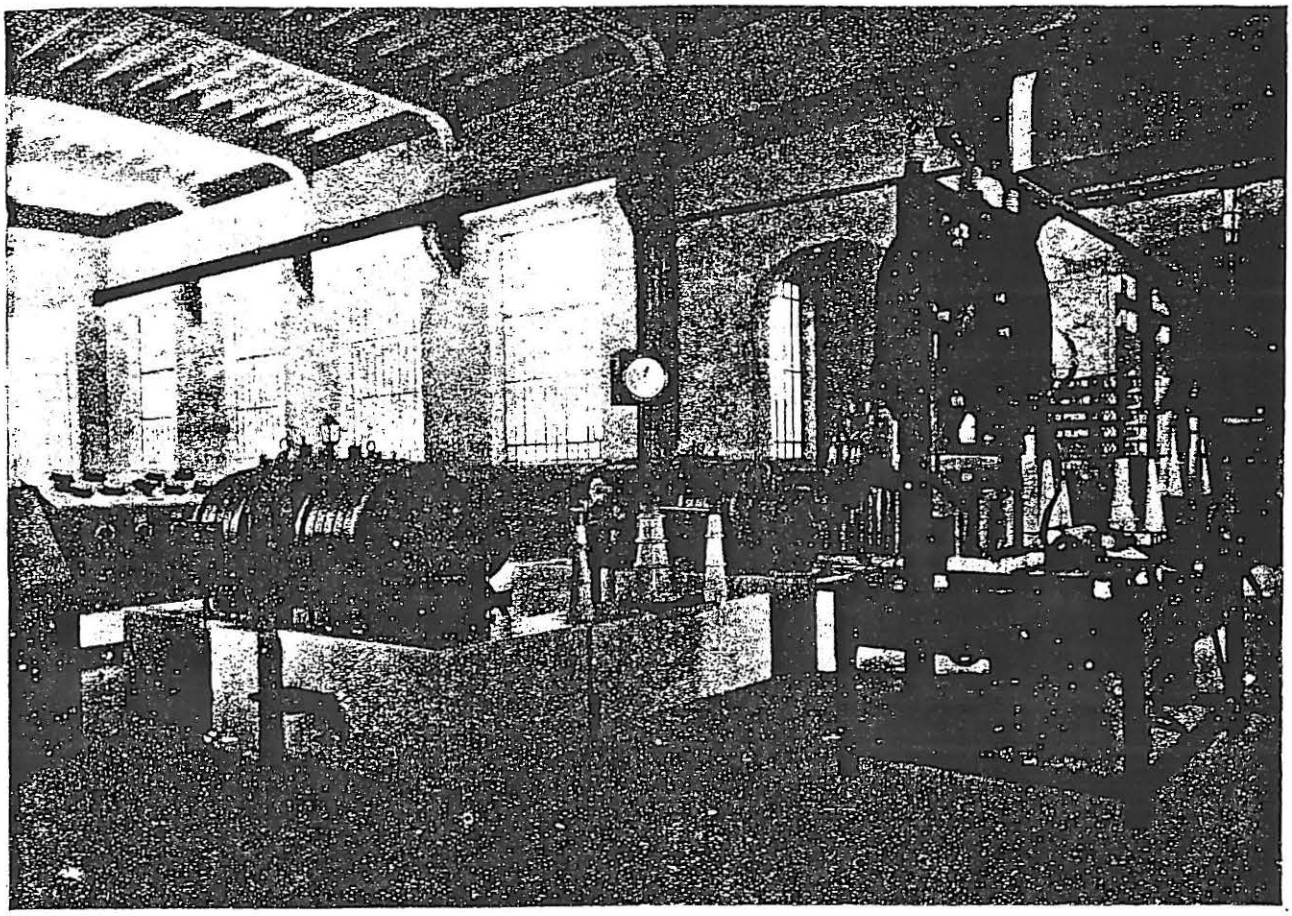


Fig. 1. Duplicate arcs installed at the Lyons station.

THE POULSEN ARC

By "INVICTUS"

A simple explanation of the transmitter which is most widely used for long-distance wireless transmission.

AT the present time the Arc is the most widely used type of transmitting apparatus for high-power, long-distance work. It is estimated that the Arc is now responsible for over 80 per cent. of all the energy being radiated into space for wireless purposes, leaving amateur stations out of consideration.

The Arc was the first successful transmitter of the Continuous Wave system, the overwhelming advantages of which have now rendered the Spark system obsolete. Briefly, the advantages of the Continuous Wave system are :

(1) The great sensitiveness of the receiving apparatus which can be employed.

(2) The ability of the transmitting apparatus to supply the largest high-frequency currents.

(3) The non-production of excessively high voltages even with these high-frequency currents.

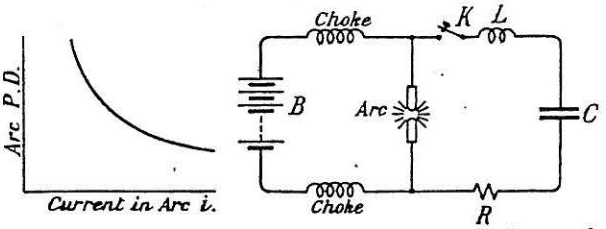
(4) The extreme sharpness of "tuning" giving greater efficiency and freedom from interference by other stations.

(5) Control of the pitch of the note of the signal by the receiving operator to suit the requirements of his instruments and his ear, and to make the signal distinguishable from noises due to atmospheric strays, etc.

(6) The less absorption of continuous waves over long distances.

across the Arc is reduced. With a decrease of current the potential difference rises. This is shown graphically in Fig. 5, which represents readings observed by connecting a voltameter and an ammeter in circuit with a D.C. Arc.

Let us consider now what will happen when the oscillation circuit is connected across the



Figs. 5 and 6. The characteristic curve and fundamental circuit used with the arc.

terminals of an Arc, as in Fig. 6. Current will flow into the condenser, its growth being retarded by the inductance L as before : but, since the choke coils have a greater inductance than L, the current flowing into the condenser is mainly shunted from the Arc, there being only a small increase in the current drawn from the D.C. supply. The current in the Arc being reduced, the P.D. across the Arc will rise (Fig. 5), and this hastens the charging of the condenser. The inductance L prolongs the charge and causes the condenser to be overcharged as already explained. The condenser will then discharge through the Arc, increasing the current through the latter and therefore reducing the P.D. across the terminals. As a useful analogy to this action the escapement of a watch may be considered. The hair-spring and weighted rim represent the capacity and inductance respectively of the oscillation circuit and will oscillate in the same way as the latter if their equilibrium is disturbed. In a watch these oscillations are made continuous by steady pressure in one direction from the mainspring, which corresponds to the D.C. supply to the Arc ; he Arc itself being represented by the mechanism which gives an impulse to the system once per cycle.

The natural oscillations first set up in the circuit are maintained, and their amplitude is increased until the energy lost, both in the antenna circuit and the Arc, equals that supplied. The Arc length is adjusted so that the supply current, or the antenna current, is a maximum for a given voltage. If the current is greater than required it is reduced by lowering the supply voltage.

In Duddell's " Singing Arc " the oscillations ordinarily produced were of audible frequency. In order to work on frequencies of 300,000 cycles per second, the hysteresis, or inertia from all causes, of the Arc has obviously to be very small —much smaller than that possible with an ordinary Arc between carbon electrodes. In a part of the extremely short time available for one complete cycle, the gas between the electrodes has to be de-ionized, and the difficulty of this is increased by the emission of electrons from the electrodes if they remain incandescent.

The Poulsen Arc

Dr. Poulsen's modifications of the Duddell Arc consisted of maintaining it in an atmosphere of hydrogen, between a cathode of carbon and a cold metallic anode, and in a transverse magnetic field. These all have for their object an increase in the power and frequency of the oscillations produced. The atmosphere of hydrogen cools the Arc and the electrodes on account of its very high heat conductivity and diffusion coefficient. It prevents the rapid burning away of the electrodes, and the formation upon them of oxides which, if formed, would be particularly active in the emission of electrons when incandescent.

The use of dissimilar electrodes also steepens the Arc characteristics. Heat is conducted rapidly away from the anode by making it of copper and by internal water cooling. Rotation

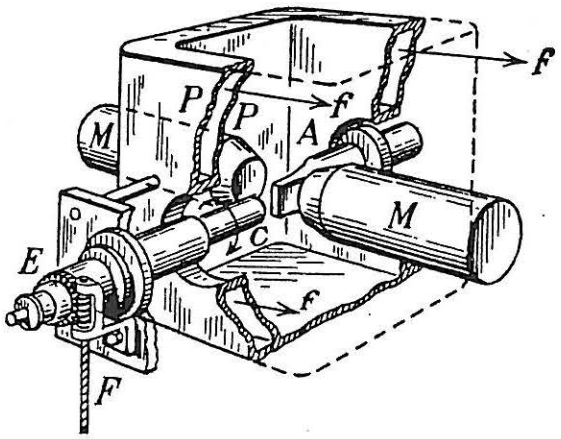


Fig. 7. A diagrammatic representation of the interior of an arc chamber.

reduces local heating of the carbon cathode. The magnetic field allows the gap between the electrodes to be quite small. Also, it blows the ions away from the electrodes with considerable velocity until the Arc is extinguished, and, if the field and other conditions are correctly adjusted, one Arc is extinguished just as another is struck between the electrodes. The essential parts of a Poulsen Arc are indicated in Fig. 7.

(7) The practicability of working at high speeds.

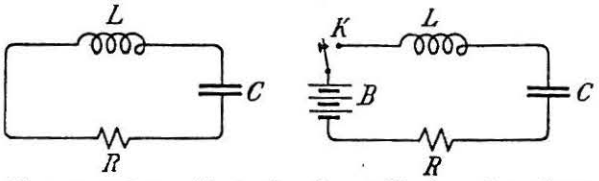
(8) The high efficiency of the plant.

A large proportion of the wireless services are now being worked by the Arc. In addition there are many others of which it is not possible to give details in the limited space of a short article. There is, for example, a new G.P.O. station at Northolt, Middlesex, whose 450-ft. masts can be seen from the Great Western Railway main line. Northolt (call sign GKB) works with Rome (call sign IDO), another Arc Station, and with a number of European countries. Leafield (GBL), near Oxford, the first station of the Imperial chain, is now equipped with Arcs and transmits a regular wireless news service to ships at sea, over distances of 5,000 miles, being read in Canada, India, South Africa, Australia, and New Zealand. Leafield's transatlantic service for news agencies is reported as being the fastest in the world. Readers will recognise on a map many of the high-power stations whose C.W. Morse they are picking up. In addition to those named, of which IDO is probably a favourite, some of the best-known stations are Eiffel Tower (FL), Lyons (YN), Cairo (SUC), and Nantes (UA) equipped by the Elwell Company, the American stations equipped by the Federal Telegraph Company, Annapolis (NSS) for example; Bordeaux (LY) in France also is using Federal Arcs, of 1,000 kw.

The development of the Poulsen Arc falls naturally into three phases, the first being the late Mr. Duddell's discovery of the "Musical Arc," from which, under certain conditions, oscillatory currents could be obtained, the next being Dr. Poulsen's modifications, by which it became possible to raise the frequency and power of these oscillations, and the third phase, following these fundamental discoveries, being the gradual development of a reliable and efficient system by accumulated experience and the application of sound engineering practice.

The Duddell Arc

To understand the working of the Arc let us consider an ordinary oscillation circuit, *i.e.*, one containing inductance and capacity, and but little resistance (Fig. 2). Let a certain D.C. voltage be applied as in Fig. 3. When the switch is closed the condenser will be charged, but the inductance will retard the growth of current, so that the charge will occupy a small but definite amount of time. When the charge produces a P.D. in the condenser nearly equal to that of the supply voltage, the charging current will tend to decrease, but the electromagnetic energy stored in the inductance will prolong the current flow, and as a result the condenser will be overcharged: its P.D. will then be greater than the supply voltage, and, after the interval during which the inductance is producing this



Figs. 2 and 3. Illustrating the application of a direct-current potential to a circuit containing inductance and capacity, but little resistance.

overcharge, will discharge back through the circuit. The inductance will behave as before, first retarding the discharge and then causing it to overshoot, recharging the condenser in the opposite sense. This cycle will be repeated, but the energy represented by succeeding oscillations will be diminished by losses and the rate of diminution will depend upon the effective resistance of the circuit. In other words, we have the well-known damped oscillatory

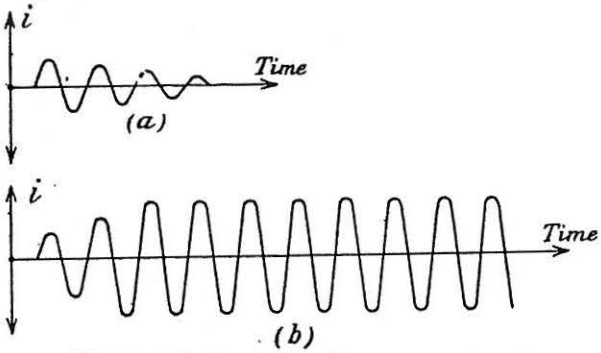


Fig. 4. The damped oscillatory discharge of a condenser.

discharge of a condenser (Fig. 4), and the frequency of these oscillations is approximately

$$f = \frac{1}{2\pi\sqrt{LC}}.$$

In order to make these oscillations continuous, energy must be supplied continuously to the system to make up for that lost, and this is done by connecting the circuit across the terminals of an electric Arc which is fed from a D.C. supply through choke coils.

An electric Arc is in effect a gaseous conductor whose diameter varies so that with an increase of current the sectional area increases and the resistance falls to such an extent that the potential



DR. FREDERICK K. VREELAND, THE AUTHOR OF THE NEW CIRCUIT.

If we are to receive a full frequency band, or spectrum, of 20 kilocycles width, including modulation frequencies up to 10,000 cycles, obviously the bands of two modulated waves of 20 kilocycles apart will meet with no space between them.

It is claimed that the band selector developed by Dr. Vreeland meets these three stated conditions, i.e., fidelity, selectivity and simplicity. It comprises, in summing up, a system of reactances so related to each other that they are mutually balanced, not merely at a single frequency, as in the case of the ordinary tuned circuit, but also at any frequency within a given band. At any frequency outside of this band the reactances are not balanced and the unbalanced reactance is high.

A Repetitively Operable, High-Current Interrupter

R. F. CARISTI, MEMBER, IEEE, AND DAVID V. TURNQUIST, MEMBER, IEEE

Abstract—A series of fast-acting and repetitively operable bimodal gas discharge switches capable of both the initiation and the interruption of high pulse currents at high-voltage levels has been designed, built, and tested. Based on hydrogen thyratron technology, these switches retain most of the characteristics of thyratrons when switching from the open to the closed state. In addition, the interruption of high currents against high source voltages is achieved when an externally generated, pulsed magnetic field is transversely applied to the current by means of a plasma–field interaction region built into the device. The interruption process is rapid (typically requiring less than 10 μs), complete (current is reduced to zero), and permanent (the current in the device does not restrike even when the field pulse terminates).

In general, operation at lower voltages allows the interruption of higher currents for a given magnetic field energy. Typical data are the interruption of 1000 A against 15 kV with a field energy of 8 J, and 100 A against 50 kV with a field energy of 33 J.

The theory, design, and construction of such switches are described, and the results of various parametric studies are discussed. It is shown that the voltage level of the interruption is the dominant factor affecting both the conduction and interruption characteristics of the device. A unique interaction region geometry that markedly reduces magnetic field energy requirements is described. It is shown that with proper interaction region design, the voltage drop across the switch during conduction is only about 2 percent of the applied voltage for a switch capable of opening against 50 kV.

The device is scalable to various voltage and current levels, and has an inherent repetition rate capability of the order of 10 kHz.

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I. INTRODUCTION

MANY APPLICATIONS exist for a high-voltage, high-current switch that can function in both the normally open and normally closed modes. Ideally, such a device should be capable of rapidly changing from one mode of operation to the other, switch at significant repetition rates, operate with a reasonably low forward voltage drop and dynamic impedance, and require minimal triggering energy to open or close.

These requirements can be met by a hydrogen thyratron

when it is properly modified for magnetically controlled current interruption. The following discussion describes a class of thyratron interrupters that can efficiently and reliably operate at significant power levels and switching rates.

II. Background

For many years, the term "interrupter" referred almost exclusively to electromechanical devices (some having magnetic and pressurized gas arc-blowout features) whose function was to interrupt direct or alternating currents against power line voltages [1]. In high-voltage dc and pulse circuits, the need for an openable and closable switch capable of operation at any significant repetition rate was generally met by high-voltage vacuum tubes [2]. Work continues to this day to increase the interruption capabilities of low repetition rate, high-power switches such as vacuum interrupters [3], [4]. High-efficiency power grid vacuum tubes and beam power switch tubes are also still being developed [5], [6].

Vacuum interrupters are physically large and slow. In general, they are suited to operation only at very low repetition rates. High vacuum electronic devices necessarily operate with significant forward voltage drops and significant dynamic impedances. An obvious need has thus existed for an openable and closable switch that could operate at high repetition rates and yet maintain a reasonably low forward drop and dynamic impedance.

As a result, considerable work has been done to investigate the properties of various types of high-voltage switches having an interrupting capability. Among these are the crossed-field closing switch, whose interrupting characteristics have been investigated by Lutz and Hofmann [7], and the magnetically operated vacuum arc as reported by Gilmour and Lockwood [8].

The use of a pulsed magnetic field to effect the rapid interruption of a discharge in hydrogen was reported by Turnquist [9] and later by Thomas *et al.* [10]. Their work provided the precedent for using pulsed magnetic fields to interrupt currents in devices that were basically hydrogen thyratrons. Further work with thyratron interrupters (typical interrupted currents being less than a few hundred amperes against 15 kV or less) was later reported separately by Shackleford [11], Weiner [12], and Wheldon [13].

We have previously reported the interruption (in a hydrogen thyratron) of 600 A against 20 kV [14]. In the present discussion, we describe the interruption of 1000 A against 15 kV and 100 A against 50 kV using a hydrogen thyratron interrupter inherently capable of pulsed operation at 10 kHz.

III. Principle of Operation

When a current I flows in an element of differential length dl located in a magnetic field of intensity B, a differential force of magnitude dF is exerted on the current element in accordance with the relation.

$$dF = IBdl \sin \theta \tag{1}$$

where θ is the angle between the direction of the current element and that of the magnetic field [15]. The resulting force acts normal to the plane containing both the current element and the magnetic field, and it is directed such that the current element, the magnetic field, and the resulting force form a right-handed set [15]. In vector notation then

$$dF = Idl \times B. \tag{2}$$

Equation (2) is absolutely general and thus applies under all conditions of time and space. The vector quantity Idl may be a time-dependent or time-invariant discharge in a hydrogen thyratron, and the vector B may be a pulsed magnetic field of peak intensity B. In any event, when Idl and B are normal to one another, the magnitude of the force dF will be maximized.

Assume that an otherwise standard hydrogen thyratron is modified to include a suitably designed region wherein its conducted current and an externally generated pulsed magnetic field can be made to interact according to (2). If the tube is conducting and a suitable pulsed field is applied, the hydrogen plasma will be driven against the walls of the interaction region and the tube current will cease to flow [12]. If this condition of zero current is maintained for a period long enough so that the grid-anode region of the tube can recover its voltage holdoff capability, the subsequent termination of the field pulse will not then result in the resumption of tube current, i.e., a permanent interruption will have occurred.

If the tube is then triggered in the normal fashion, it will commutate and conduct as would any thyratron. Alternatively, various "keep-alive" schemes can be employed such that the tube will automatically conduct unless the pulsed field is present.

With proper design, such a system can be made to function as a repetitively operable bimodal switch having a reasonable forward voltage drop and a low dynamic impedance.

IV. Physical Embodiment

Various schemes have been devised to incorporate the required interaction region into the thyratron [11]-[14], [16]. Fig. 1 shows a thyratron interrupter of a general design that is capable of multimegawatt interruptions. The device is of ceramic-metal construction and consists basically of three sections—two cylindrical compartments joined by a specially configured field-plasma interaction channel (fabricated from alumina) described in detail further below. The large cylinder contains the cathode, hydrogen reservoir, and the heater assemblies, while the smaller cylinder contains the holdoff section. For tubes rated above 30 kV, a gradient grid is usually used in the holdoff section as shown in Fig. 1 to ensure reliable holdoff at high anode voltages.

Locating a relatively long interaction channel in the control grid-cathode space as shown in Fig. 1 mandates the use of higher trigger voltages than those required for a standard tube having the same holdoff and conduction capabilities. This location for the interaction region nonetheless provides the best overall triggering characteristics [16]. Through the use of appropriate keep-alive discharges, the anode delay time, t_{ad}, and the delay time jitter, t_j, can be made comparable to those of a standard thyratron, with t_{ad} less than 200 ns and t_j less than 5 ns being readily achievable [17].

Interrupters of the type shown in Fig. 1 are usually filled

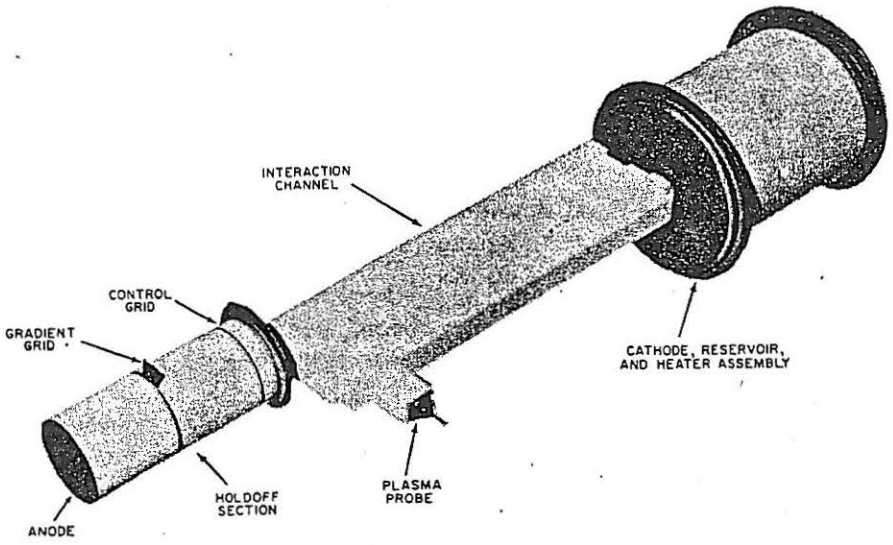


Fig. 1. A typical thyratron interrupter. The tube shown has interrupted 100 A against 50 kV and 1000 A against 15 kV.

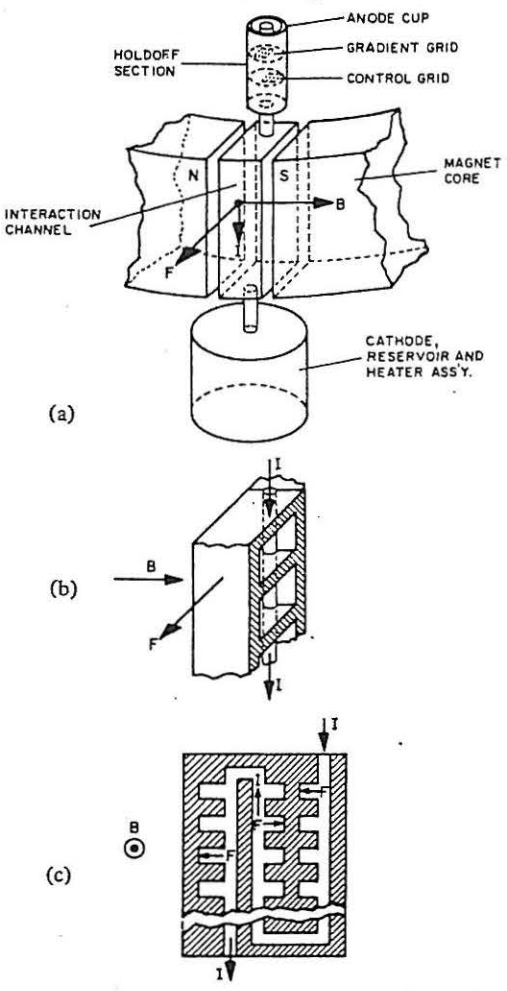


Fig. 2. Interrupter mounting and channel geometry. The "plasma chutes" reduce the magnetic field required to achieve interruption, and folding the channel makes better use of the available magnetic field energy.

with hydrogen and are typically operated in the same pressure regime as are standard tubes, i.e., 0.2–0.5 torr.

For the device shown in Fig. 1, the total external width of the interaction channel is 2 in, its thickness, 0.500 in, and its active length (grid-cathode direction), 7 in. For operation, the interrupter is mounted such that the interaction region fills an air gap slightly wider than 0.500 in between the pole faces of an electromagnet. The pole faces are 2 in wide and 6 in long, so the interaction region is subjected to a substantially uniform flux density normal to the plane containing the tube current. Depending on the direction chosen for the magnetic field, the force acting on the tube current will propel the discharge in one direction or the other along the 2-in channel dimension.

Such an arrangement is shown in Fig. 2(a) where the tube current I (a scaler quantity) has been treated as a vector for purposes of the illustration. Fig. 2(b) shows the essence of the interaction channel's design. One wall has been "removed" to show the details of the channel's interior. The channel consists of a bore through which the tube current normally flows, and a series of voids or "plasma chutes" into which the discharge can be magnetically driven. Fig. 2(c) shows a section through the center of the bore such that the direction of the applied field is toward the reader. As shown in Fig. 2(c), the effective length of the interaction channel can be increased by folding the bore and the plasma chutes in the manner shown. As discussed further below, such folding allows interruption against higher open-circuit voltages. It also allows a better utilization of the available magnetic field energy. When the channel is folded, the direction of the vector Idl is reversed in alternate sections of the channel, so the location of the chutes with respect to the bore must be reversed as shown.

A cross section taken through the center of a two-section, single-gap device rated at 30 kV is shown in Fig. 3. This tube was equipped with both long and short chutes to permit an investigation of the effects of chute length on interruption efficiency. The discharge could be driven into either the longer or shorter chutes depending on the direction chosen for the magnetic field.

Tubes having single-, double-, and triple-length channels have

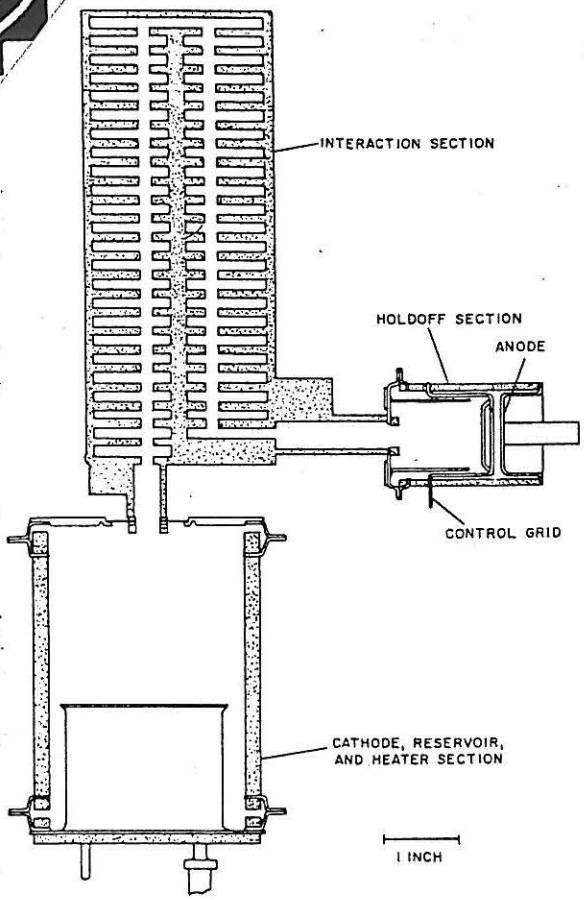


Fig. 3. Section taken through center of a two-section interrupter. The discharge could be driven into the longer or shorter chutes depending on the direction chosen for the magnetic field.

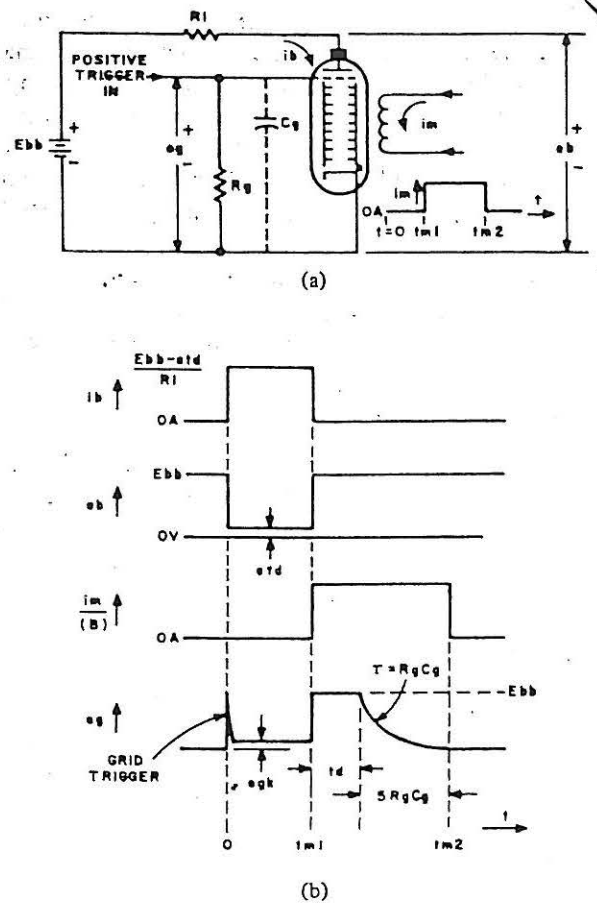


Fig. 4. Interrupter circuit and ideal waveforms. If the duration of the applied field exceeds the total of the deionization time and the grid decay time, the discharge will not restrike.

been built and tested. The tube shown in Fig. 1 is a triple-section device that has been successfully operated at 50 kV.

V. Typical Interrupter Waveforms

Ideal Case

In the circuit of Fig. 4(a), assume that an ideal magnet current pulse could be generated as shown. A total tube drop, e_{td}, total grid and column drop, e_{gk}, and a holdoff section deionization time, t_d, are assumed for the interrupter, as is an effective grid-to-ground stray capacity, C_g. If the tube is triggered at $t = 0$ and the magnet current, i_m, exceeds the level required to achieve interruption, the circuit waveforms will be as shown in Fig. 4(b). (Note that the grid is lifted to E_{bb} upon interruption.) Also, if $t_{m2} - t_{m1}$ is greater than the sum of t_d and $5\,R_gC_g$, the grid will be at ground at the end of the magnet pulse. Permanent interruption will have been achieved.

Practical Case

A practical test circuit is shown in Fig. 5(a). R_m is chosen to provide a critically or slightly underdamped i_m, and the magnet pulse is electronically delayed. As seen in the oscillogram of Fig. 5(b), the anode drops to e_{td} as the current rises to its peak value. The grid trigger is too narrow to be

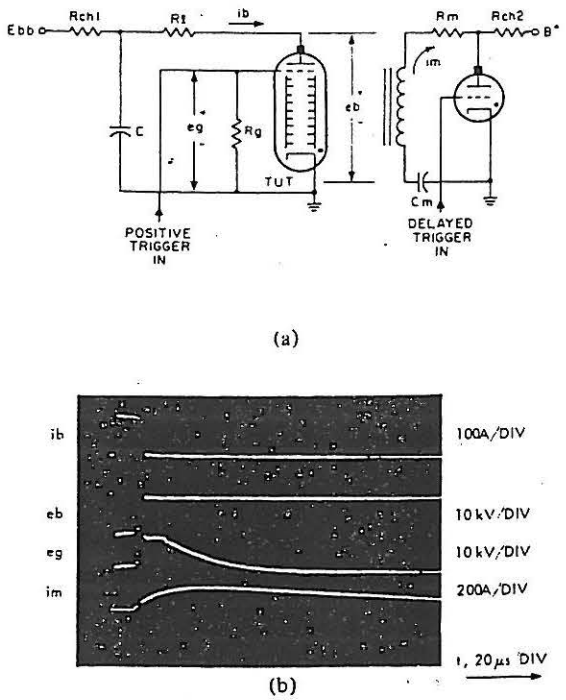


Fig. 5. Interrupter test circuit and waveforms. Note that the interruption is permanent.

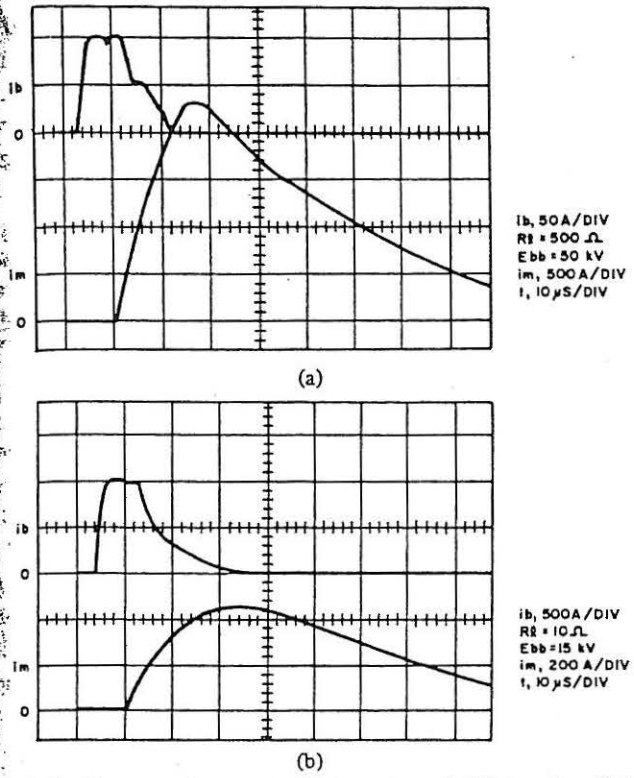


Fig. 10. Oscillograms showing the interruption of 100 A against 50 kV (a) and 1000 A against 15 kV (b). Core saturation is imminent in the 50-kV case. The discharge did not restrike.

TABLE I
TYPICAL INTERRUPTION EFFICIENCIES, TRIPLE-SECTION TUBE, TYPE C

Ebb (kV)	ib (A)	Load Power (Megawatts) (Note 1)	Interrupting Energy (Joules) (Note 2)	Interruption Efficiency (Megawatts/Joule)
50	100	5.0	32.8	0.15
44	180	7.8	11.3	0.69
32	305	9.3	7.77	1.20
26	480	11.5	5.83	1.97
18	700	9.8	1.43	6.85
15	1000	10.0	1.20	8.33

Notes:
1. The load power is less than the product of Ebb and ib because of the high tube drop at high ib.
2. The interrupting energy is calculated from Eq. 3.

dependence of B_q on the voltage is strongly nonlinear. The dependence of B_q on the tube current is much less pronounced, and currents well in excess of 1000 A were readily interrupted against voltages less than 15 kV.

VIII. Relationship Between Tube Drop and Open-Circuit Voltage

For interrupters of the general design being discussed, a rule-of-thumb relation can be derived for the tube drop as a function of the maximum open-circuit voltage.

The combined drop of the cathode and holdoff sections is typically 100–130 V, whereas the channel drop can be of the order of a kilovolt for a high-voltage device. The total tube drop is thus dominated by the channel drop. The voltage gradient along the channel is of the order of 20 V/cm. To a first approximation, then

$$e_{td} \approx e_{cd} \approx 20\, l \tag{4}$$

where l is the channel length in centimeters.

A conservative design value for the electric field in the channel during interruption is 900 V/cm. Thus for a given open-circuit voltage E_{bb}, the minimum permissible channel length is

$$l = \frac{E_{bb}}{900}\ (\text{cm}) \tag{5}$$

where E_{bb} is in volts.

Combining (4) and (5)

$$e_{td} \approx \frac{20}{900} E_{bb} = 0.022\, E_{bb}. \tag{6}$$

For a given E_{bb}, doubling the channel length to provide a margin of safety against channel arcing (or to reduce the magnetic field energy required for interruption) will, to a first approximation, increase the tube drop to 4.4 percent of E_{bb}.

IX. Potential Capabilities of Thyratron Interrupters

Interruption Efficiency

Decreasing the magnetic field rise time by 35 percent has been shown to decrease the magnetic field required for interruption by at least a comparable amount, with the improvement being most pronounced at higher electric fields in the interaction channel [14]. This implies that the interruption efficiencies observed for the triple-section tubes at the higher open-circuit voltages do not necessarily reflect the ultimate capabilities of these devices.

The interruption process is inherently rapid [9], [10]. We regularly observed interruption in times of the order of 10 μs (Figs. 5 and 10), and 2-μs interruptions have been achieved. For the experimental data reported herein, the slope of the magnetic field was of the order of 10 kG in 10 μs. The overall conclusions are that faster rising magnetic fields are achievable, that the interruption process can respond to faster rising fields, and that interruption efficiencies higher than those already demonstrated are indeed possible with an improved magnetic field generator.

Pulse Repetition Rate

It is important to distinguish between the terms "pulse repetition rate" and "interruption rate." In some applications, the interrupter may be required to operate at some arbitrary pulse repetition rate (and corresponding power level), but to interrupt only upon a relatively infrequent command. In other cases, the interrupter may be required to interrupt every pulse. In still others, the interrupter may normally conduct

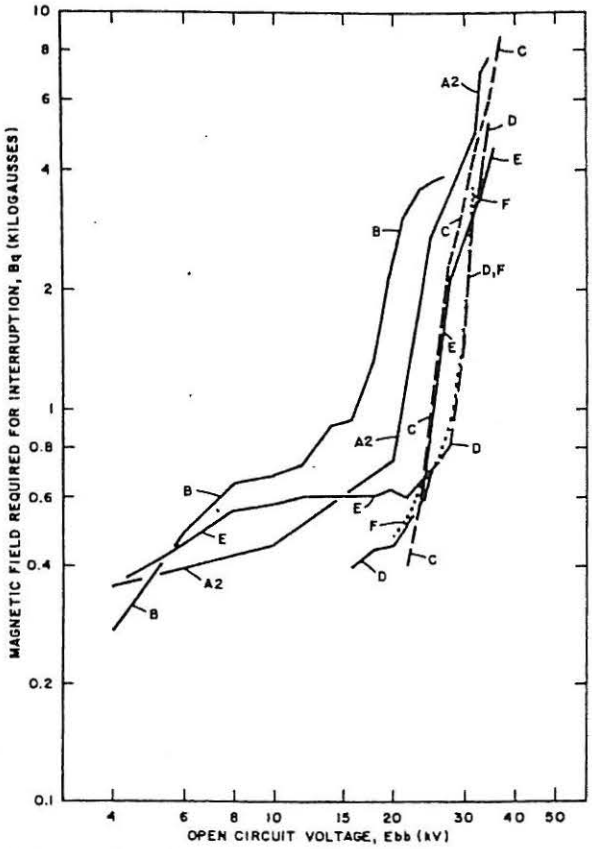


Fig. 8. Interruption characteristics for the triple-section tubes. All tubes (except type B) outperformed the type A as had been expected.

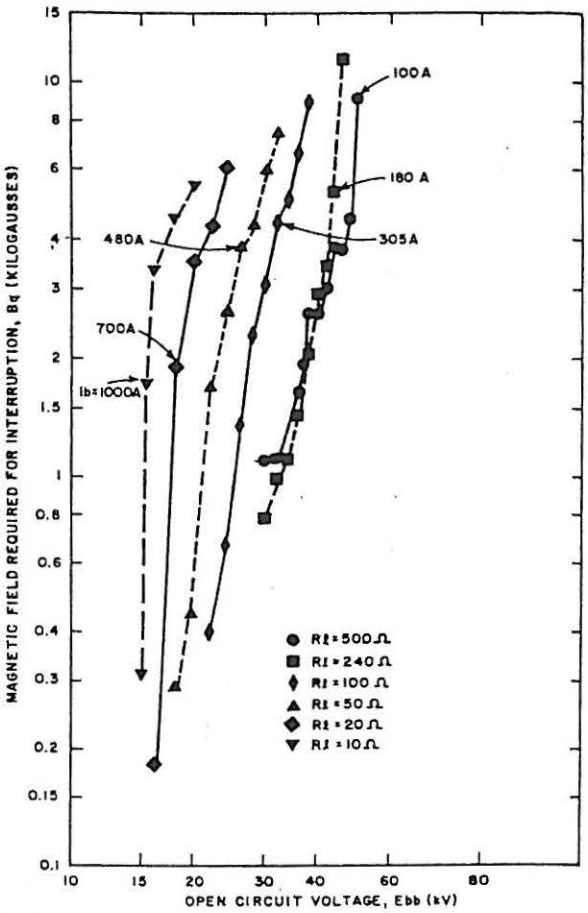


Fig. 9. Interruption characteristics for the triple-section type C at high open-circuit voltages. The indicated currents are measured values.

shown in Fig. 8 for open-circuit voltages up to 35 kV and a load resistance of 100 Ω. All tubes (except the type B) outperformed the type A as expected. (The narrow-bore type B was dominated by self-interruption effects, and its performance was in general erratic.) Types D, E, and F were the better performers of the series. This suggests that maximizing the number of chutes (D), setting the chutes at an angle (E), and minimizing the width of the chutes to reduce the plasma volume (F) are all conducive to efficient interruption.

Except for type B, the total forward drops of the triple-section tubes were substantially the same and averaged 1000 V at a pulse current of 10 A and a typical operating pressure of 320 μm. The two-gap holdoff section and the cathode section contributed a total of 130 V to the total tube drop. The column drops averaged 870 V, or 16.3 V/cm. For the type B, the corresponding data are $e_{td} = 1300$ V and a gradient of 21.9 V/cm.

The type C was selected for an investigation of high current interruption at very high voltages. Detailed interruption data for this tube are shown in Fig. 9 for various load resistances and voltages up to 50 kV, the design limit of the tube. As previously discussed, the tube current cannot be inferred directly from the interruption characteristic without a knowledge of the instantaneous tube drop. The various currents called out in Fig. 9 are measured values, however, and the tube drop at each point can be inferred from the currents shown, the load resistance, and the open-circuit voltage.

The currents indicated for each value of load resistance in Fig. 9 are clearly not necessarily the highest currents interrupted with that particular value of resistance. They have significance, however, in that they are representative of the maximum power level for the corresponding load resistance where tube operation was flawless, i.e., the interruption was both complete and permanent. (The tube current was reduced to zero, and the discharge did not restrike.) Representative oscillograms showing such performance appear in Fig. 10, which shows the interruption of 100 A at 50 kV (Fig. 10(a)) and 1000 A at 15 kV (Fig. 10(b)). Note in Fig. 10(a) that saturation of the magnet's core is imminent as shown by the distortion in the waveform of i_m.

Table I shows the interruption efficiency in terms of interrupted megawatts at the load per joule of magnetic field energy delivered to the interaction channel for each value of current and load resistance indicated in Fig. 9. Note from Table I that for the cases shown, the load power varies by a factor only slightly more than two, the current by a factor of ten, and the circuit voltage by rougly a factor of three. Yet the interruption efficiency increases from 0.15 in the high-voltage case to 8.33 in the low-voltage case (a factor of 56), and does so in spite of the tenfold increase in tube current. It is clear from Table I that the interruption efficiency is dominated by the voltage level of the interruption, and that the functional

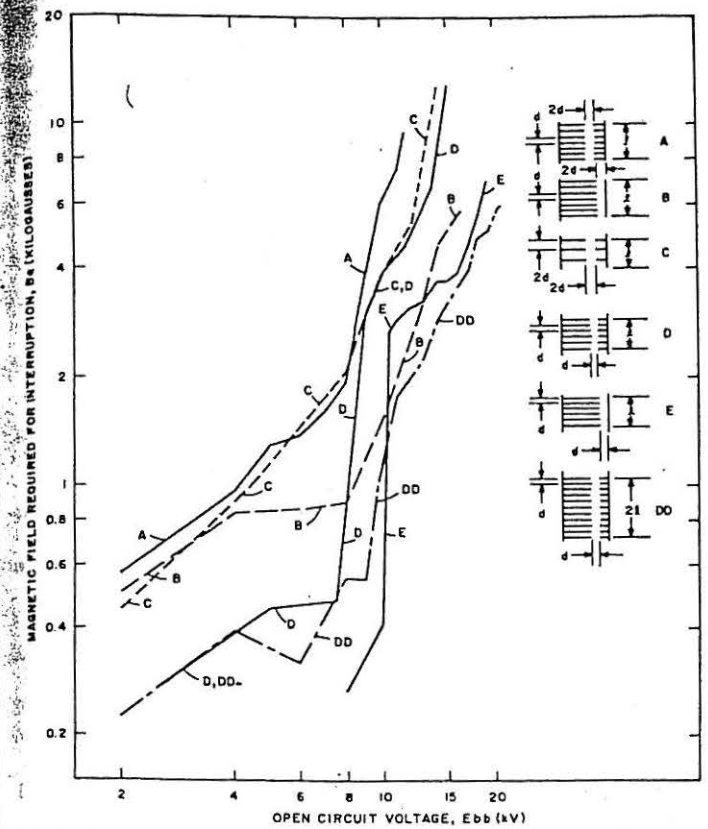
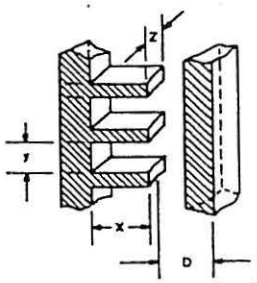


Fig. 6. Interruption characteristics for single-section tubes and double-section tube of Fig. 3. The type *E* channel geometry was highly effective, and folding the channel (type *DD*) produced the expected results.



Type	Bore Diameter D	Chute Depth x	Chute Height y	Chute Width z	Notes
A	0.150	0.250	0.150	0.300	Base Tube
B	0.100	0.250	0.150	0.300	Small Diameter
C	0.150	0.150	0.150	0.300	Minimum Reservoir
D	0.150	0.250	0.100	0.300	Maximum Chutes
E	0.150	0.250	0.125	0.300	Chutes at 45°
F	0.150	0.250	0.150	0.150	Minimum Reservoir

- All dimensions in inches.
- All sections 7 inches long.
- Three sections per tube.

Fig. 7. Channel geometry for triple-section tube. Each deviation from the base (type *A*) was in a direction expected to decrease the field requirements.

knowledge of the corresponding total tube drop. The tube drop is a function of both the tube current and the gas pressure, and owing to the long interaction channel, the tube drop can be significant at high tube currents. The tubes of Fig. 6 were designed to serve as a protective component to be operated in series with the device being protected. As such, they were to operate at a normal peak pulse current of a few tens of amperes, and to interrupt the circuit current if the load malfunctioned such that the peak circuit current increased to a resistance-limited 300 A.

At normal tube currents and tube pressures, the total tube drop was 400 to 450 V (depending on tube type, current, and pressure) for the single-section tubes and 850 V for the double-section type *DD*. The drop associated with the hold-off and cathode sections was approximately 100 V (total). A typical value for the gradient along the channel during normal conduction was 23 V/cm.

From the data of Fig. 6, several aspects of an optimum channel geometry were inferred. Narrow-bore tubes were, in general, more efficient than wide-bore tubes. This result was consistent with the earlier observations of Turnquist and Simon for unchuted tubes [16], and also consistent with the self-interruption characteristics to be expected for channels of such cross sections and gas pressures [14]. The presence in the channel of an unchuted surface enhanced the interruption process, probably by precluding the existence of plasma reservoirs that could supply plasma to the discharge during the interruption. The type *C*, with its relatively open internal structure, was one of the least efficient of the series, indicating that a large number of chutes was indeed helpful to the interruption process.

The double-length *DD* was, as expected, the most efficient tube of the series. This device successfully interrupted 600 A against 20 kV with a magnetic field energy of less than 8 J. Its performance demonstrated that multiple, folded interaction channels better utilized the available magnetic field energy while simultaneously allowing interruption against higher voltages for a given electric field in the channel during the interruption process.

Triple-Section Tubes

A series of triple-section tubes (Fig. 2(c)) was designed and built to achieve interruption against higher open-circuit voltages. The channel geometry was patterned after that of the most successful of the single-section tubes of Fig. 6, namely, the type *E*. The channel geometry (per section) and the applicable physical dimensions are shown in Fig. 7. Each section was 7 in (17.8 cm) long, and thus designed to operate at an electric field as high as 937 V/cm when interrupting against 50 kV. Each variation from the base design (type *A*, Fig. 7) was in a direction expected to lower the interrupting magnetic field. Reducing the bore diameter (*B*) was expected to enhance self-interruption effects. Decreasing the chute depth (*C*) reduced the volume of plasma available to sustain the discharge, as did decreasing the chute width (type *F*). Decreasing the chute height (*D*) increased the total number of chutes. Type *E* was a special case where the chutes were set at an angle to accommodate the assumed trajectory of the electrons during the interruption process.

The interruption characteristics for this series of tubes are

visible in the waveform of e_g, but the grid-to-ground drop, e_{gk}, which includes the drop of the discharge channel, e_{cd}, may be clearly seen. When the magnet current reaches the appropriate level, interruption rapidly ensues. The anode returns to high voltage (some charge has been removed from C by i_b), i_b drops to zero, and the grid follows the anode to the capacitor voltage, at which level it remains until deionization of the holdoff section occurs. Thereupon the grid decays exponentially to ground. Since $e_g = 0$ well in advance of $i_m = 0$, restriking does not occur. Fig. 5(b) is a time exposure showing about 10 interruptions at 2 Hz to indicate the stability of the device.

VI. Design of the Interaction Channel

Design Tradeoff

A tradeoff exists between the forward voltage drop of the interaction channel and the magnetic field energy necessary to achieve interruption. The channel drop dominates the total forward drop of the interrupter and thus its efficiency as a closed switch. The field energy determines the energy storage requirement for the magnet circuit, and this impacts the efficiency of the system as a whole.

The voltage drop across the channel has been observed to be nearly proportional to the magnetic field intensity [16]. This observation gives rise to the expectation that for a given open-circuit voltage, the field intensity necessary to achieve interruption, B_q, would vary inversely with the length of the channel. Such a relationship was reported by Thomas *et al.* [10], and later, more extensive experiments by Turnquist and Simon revealed that B_q varied as $l^{-0.75}$ where l was the length of the channel [16].

There is also a minimum channel length for a given open-circuit voltage. During the interruption, the voltage across the channel rises toward the open-circuit voltage as the tube current decreases to zero. When the interruption is complete ($i_b = 0$), the full open-circuit voltage appears across the channel. This condition prevails until the holdoff section recovers such that holdoff is transferred to the grid-anode space. It is essential that the channel be sufficiently long so that the field therein will not be excessively high during the whole of the interruption process. Too high a field will promote arc formation and restriking of the discharge.

For a given channel length and gas pressure, the forward voltage drop of the channel can be reduced by increasing the radius r of its bore. However, the dependence of e_{cd} on r is weak (e_{cd} varies as $r^{-0.5}$) [16], [18], whereas a strong and direct dependence of B_q on r has been experimentally determined [16]. The reduction in B_q observed for small-bore tubes is probably due to the tendency of a constricted gas discharge to self-interrupt or "quench," a phenomenon widely observed at the grid apertures of standard hydrogen thyratrons [19], [20]. Some relief is offered by operation at low gas pressure. This reduces the column drop and increases the propensity of the discharge to self-interrupt [20]. However, only limited gains in column drop can be realized in this manner since the dependence of e_{cd} on the tube pressure is weak, and both triggering requirements and the need for quench-free operation at normal forward currents and pulsewidths set a lower bound for the gas pressure.

The energy delivered to the interaction channel by the magnetic field is [21]

$$W_c = \frac{B_q^2}{2\mu} V \text{ (J)} \tag{3}$$

where B_q is the magnetic field intensity necessary to achieve interruption (Wb/m^2), V is the volume of the interaction channel (m^3), and μ is the permeability of the media comprising the channel, in this case $4\pi \times 10^{-7}$ (H/m).

From (3), W_c is strongly dependent on B_q. Since B_q varies as $l^{-0.75}$, it follows that long (for low B_q), thin (for low volume) channels will minimize W_c. Since e_{cd} varies as l, e_{cd} and W_c cannot be mutually minimized.

The Chuted-Wall Concept

It is clearly advantageous to devise a mechanism for reducing B_q that does not rely solely on increasing the length of the interaction channel. One method to accomplish this is to add a series of "plasma chutes" along the length of the channel's bore as shown in Fig. 2. The technique is similar to that used in the design of some types of power-line interrupters as described by Cobine [22]. The chutes are positioned along the bore such that the force acting on the plasma drives it bodily into the chutes. The presumption is that the increased and relatively cool surface area thus made available to the discharge promotes interruption by starving the plasma of electrons and ions through surface-induced recombination, although other mechanisms might be partially or even wholly causative of the interruption [16].

Early results obtained with chuted interrupters were successful in that the fields required to achieve interruption in chuted tubes were lower by two-thirds when compared with those required for unchuted tubes under otherwise identical conditions [16].

VII. Experimental Data

Single- and Double-Section Tubes

To investigate the effects of various chuting arrangements on the magnetic field required to achieve interruption, a series of interrupters was built having the channel geometries shown in Fig. 6. Types *A* through *E* had single-section interaction channels and type *DD* was the double-section folded device shown in Fig. 3. The effective channel length l was 6.1 in (15.5 cm) and the dimension "d" was 0.15 in (3.8 mm). The tubes were operated at voltages as high as 15 kV per section, so the maximum electric field in the channel during interruption was 968 V/cm.

The interruption data shown in Fig. 6 correspond to the most efficient mode of operation for each device. For tubes having a smooth wall, this means that the data shown are for the case where the discharge was driven into the chutes. For tubes having both long and short chutes, the data correspond to the case where the discharge was driven into the short chutes.

To obtain the data shown in Fig. 6, the tubes were operated in the circuit of Fig. 5, and the data shown in Fig. 6 correspond to a load resistance R_l of 20 Ω. The current interrupted at any given voltage cannot be inferred from Fig. 6 without

only direct current, with interruption of that current (or some level of fault current) being the desired mode of operation.

Fig. 5(b) shows the total of the holdoff section deionization time and the grid decay time to be 60 μs. This implies a maximum interruption rate of 16 kHz at the 100-A, 10-kV level. For the majority of our investigations (including the high-power interruptions described herein), we have observed an interrupter recovery time of the order of 100 μs, so an interruption rate of 10 kHz appears to be inherently possible.

The practical limitation on pulse repetition rate (or interruption rate, or average current) is likely to be set by channel dissipation. Two mechanisms for channel heating must be considered. The first is the power dissipated in the channel due to the forward current and the voltage gradient along the channel under noninterrupted conditions. The second is the transient power dissipated in the channel during interruption.

The average channel heating due to the interruption transient can be reduced by reducing the interruption time. This is another reason to operate with a fast magnetic rise time as discussed above in connection with interruption efficiency.

Measurements of the channel voltage gradient during conduction and the instantaneous plasma potential during interruption have shown that both are reasonably uniform along the channel's length [17] as implicitly assumed in the derivation of (6). Given this information, and assuming a safe working temperature of 600°C for high-purity alumina, we estimated reasonable heat loads for water-cooled channels with a flow rate of a few gallons per minute. We concluded that a heat load of 100 W/cm of channel length was reasonable for channels having the applicable geometry and dimensions. Since the conduction gradient is typically 20 V/cm, heat loads corresponding to an average forward current of 5 A should be feasible.

X. Summary

Magnetically controlled current interruption can be efficiently and reliably achieved in a hydrogen thyratron operating at significant power levels when the magnetic field is transversely applied to a properly designed plasma-field interaction region built into the tube. However, the addition of the interaction channel to the discharge geometry increases the total forward drop of the thyratron, and the tube drop and magnetic field requirements cannot be mutually minimized.

The addition of "plasma chutes" to the interaction channel reduces the magnetic field requirements without introducing an excessively high tube drop. Maximizing the number of chutes, setting the chutes at an angle to accommodate the trajectory of the electrons during interruption, and minimizing the "plasma reservoirs" available to sustain the discharge are all conducive to efficient interruption.

A tradeoff exists among the current to be interrupted, the voltage level of the interruption, the forward drop as a fraction of the open-circuit voltage (conduction efficiency), and the magnetic field energy necessary to achieve interruption at a given power level (interruption efficiency). The voltage level of the interruption dominates the performance of the device. Representative data for interrupted current, voltage, and the required magnetic field energy are 100 A against 50 kV, 32.8 J; 305 A against 32 kV, 7.8 J; 700 A against 18 kV, 1.4 J; and 1000 A against 15 kV, 1.2 J. Typical total tube drops are of the order of 2-2.5 percent of the rated open-circuit voltage. It is likely that the interruption efficiency can be improved at high voltage by decreasing the rise time of the magnetic field intensity.

The inherent limit on the interruption rate is set by the recovery time of the interrupter. This time is of the order of 100 μs, so the inherent interruption rate is limited to 10 kHz. The practical limit is set by the dissipation capabilities of the interaction channel. For water-cooled channels, heat loads corresponding to an average current of 5 A should be attainable.

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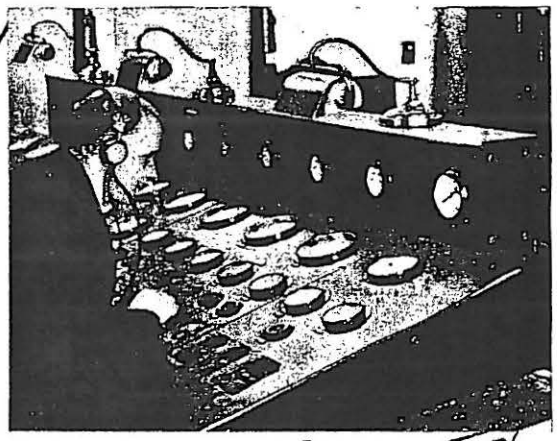
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SECTION 3

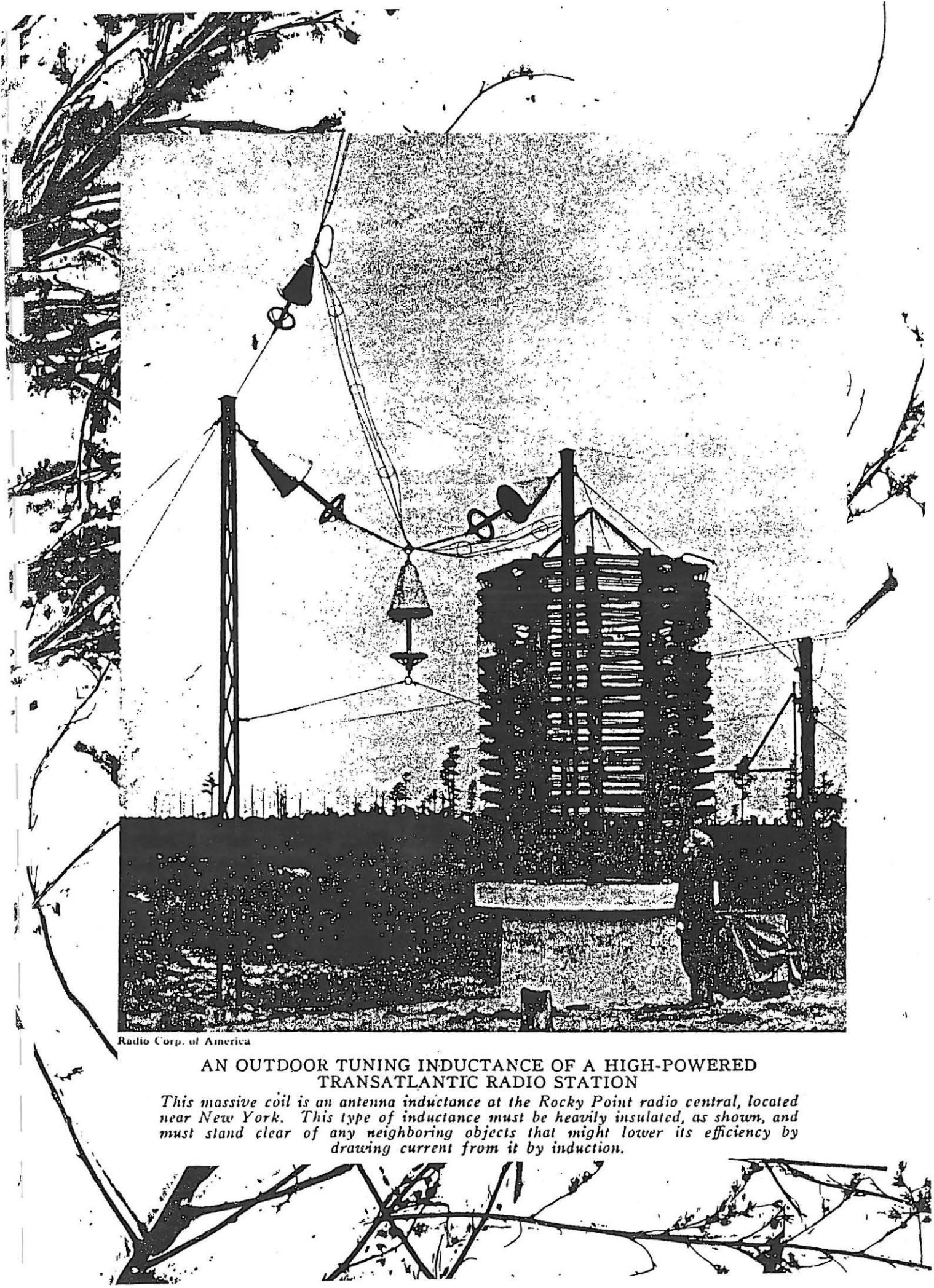
VLF ANTENNAS

courtesy A. T. & T. Co.



The Nerve Centers of the Trans-Atlantic Radiophone System

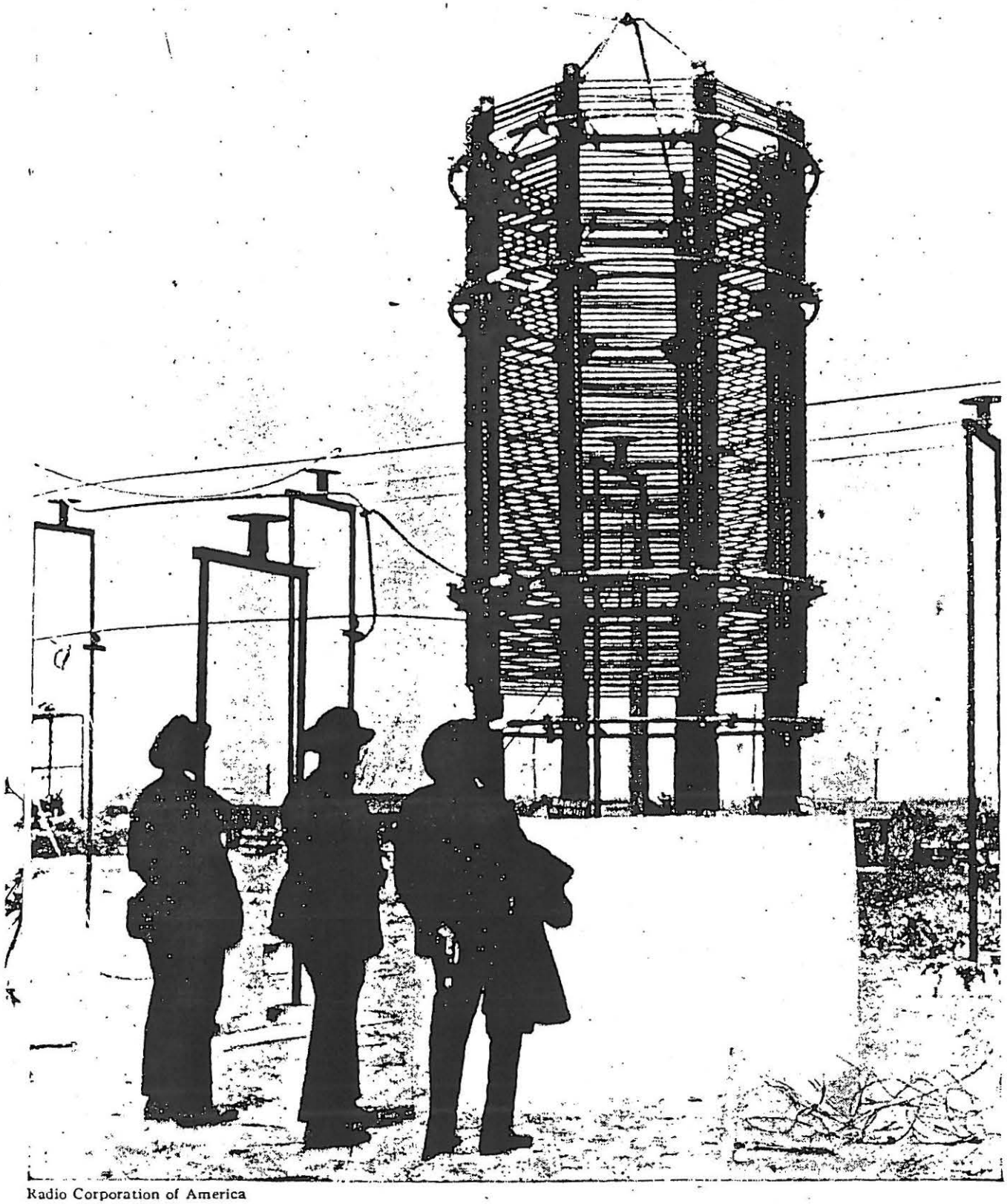
From this gigantic antenna system at Rocky Point, New York, 7,250 feet long, the radio impulses that carry your voice from the telephone in your home, when you put in a call for London, are sent out across the Atlantic ocean to sensitive radio receivers and finally to telephones in homes and offices on the other side. At the left is one of the elaborate control boards at the radio station at Rugby, England, where radio messages on that side of the water are received and retransmitted by wire. Land wires carry the messages from the central telephone exchange in New York to the transmitting station at Rocky Point. The radio receiving station at this end is at Belfast, Maine. The opening of this service to the public on January 10, 1927, was attended by great success.



Radio Corp. of America

AN OUTDOOR TUNING INDUCTANCE OF A HIGH-POWERED TRANSATLANTIC RADIO STATION

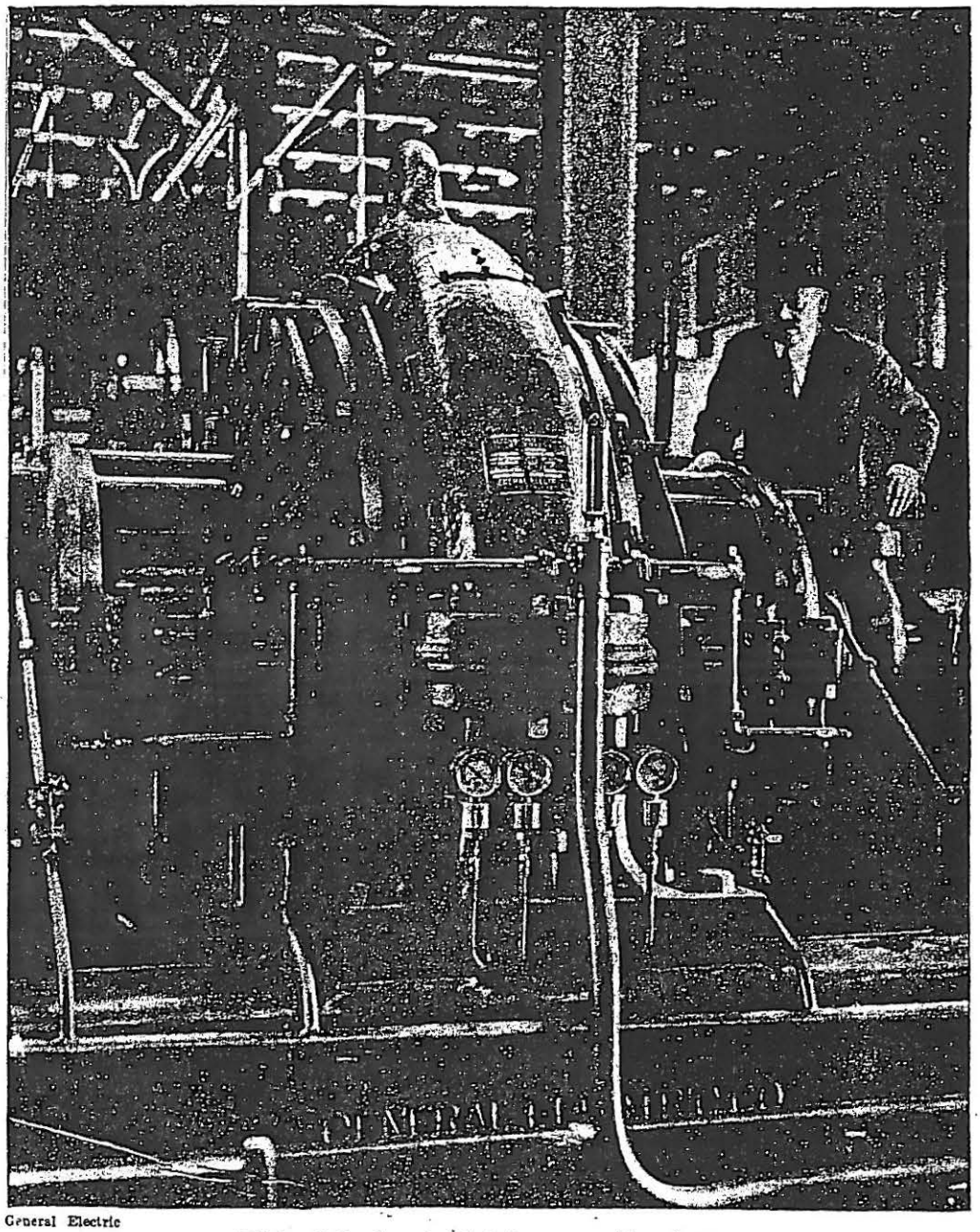
This massive coil is an antenna inductance at the Rocky Point radio central, located near New York. This type of inductance must be heavily insulated, as shown, and must stand clear of any neighboring objects that might lower its efficiency by drawing current from it by induction.



Radio Corporation of America

ONE OF THE BIGGEST COILS IN THE WORLD

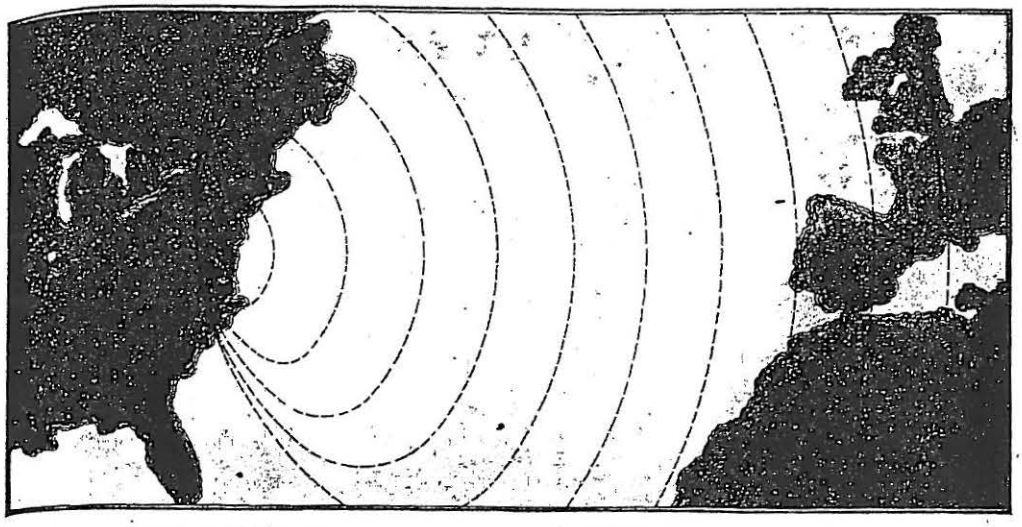
Here is shown one of the great tuning inductances used at the large central radio station at Rocky-Point, Long Island. Compare the size of the coil with height of the men standing in the foreground. If this coil were not efficient there would be enormous losses in the power surging back and forth in the huge transmitting antenna. Although your coil is tiny, if it is not properly designed the losses in it may be just as large—relatively.



General Electric

This Mechanical Monster Produces a 30,000-Meter Wave

The higher wavelengths used in transatlantic radio communication, ranging from 10,000 to 30,000 meters, are made possible by the power generated by this Alexanderson type of high-frequency alternator. Several of these whirling giants are used for energizing the antennas of the transmitting stations at Radio Central on Long Island, New York. Its inventor, Dr. E. F. W. Alexanderson, is here shown viewing his remarkable brain-child.



A PLAN FOR SPANNING THE ATLANTIC ON LOW POWER

At present transatlantic communication is carried on with high power on wavelengths up to 30,000 meters—waves which are inaudible. By using base-line antennas about 220 miles long this communication may be carried on at still longer wavelengths with waves that are audible.

THE COMING USE OF

Frequencies That We Can Hear

Experiments with audio frequency shows that its possibilities in "earth telegraphy" have scarcely been realized. Its application to the longer wavelengths is here pointed out.

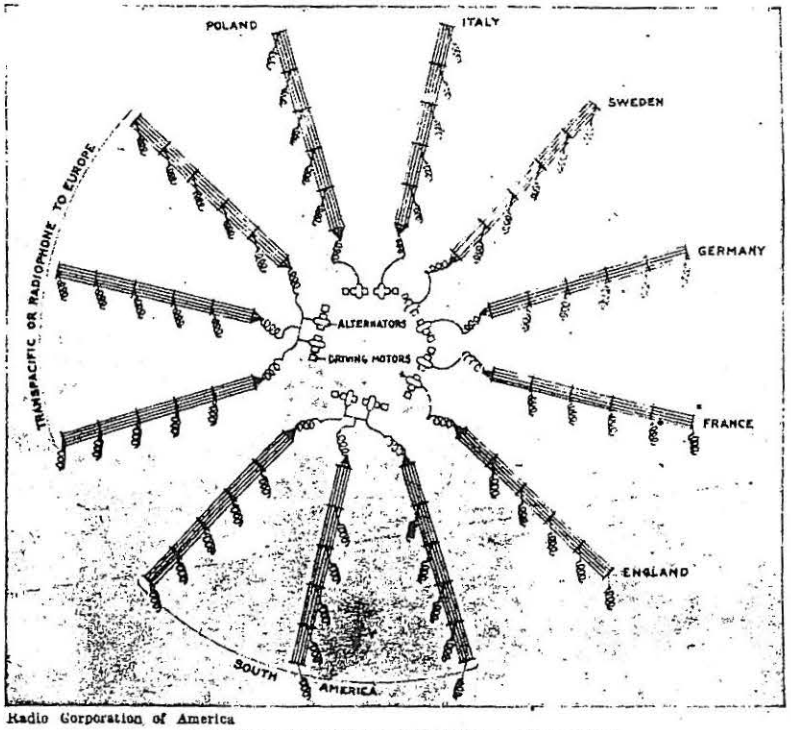
By OSCAR C. ROOS

THE temptation at the present moment is to ignore the field which modern high-power transmitting stations are approaching—the 30,000 meter wave and over; radio experimenters and the electrical world in general are directing their attention at present to very short waves. For that matter very short waves have been neglected for years; they have been used only occasionally as scientific tools in the laboratory, although Stone, Ladd and Marconi have used the shortest wavelengths—going down to two meters.

But the long wavelength—a wave, for instance, nineteen miles long which does not radiate until about five miles away from the station—is sure to be of interest.

The great drawback at present to the use of such waves is the fact that the radiant point, or rather cylinder, around a station allows less and less energy to flow out in the form of waves as the field gets weaker. The balance goes back to the antenna as the energy of a stationary wave, giving effects of distributed self inductance and capacity. This is the reason why power wires radiate very little energy at 60 cycles a second. The radiant cylinder for a vertical power wire under these conditions in New York would pass close to Atlanta, Nashville and Chicago—about 775 miles away. With such a weak field the radiation is immeasurably small.

It is worth while to dwell on the real meaning of the radiant cylinder. It is



Radio Corporation of America

A LONG WAVE ANTENNA SYSTEM

How the powerful high frequency alternators are connected to the multiple-tuned antennas at Radio Central. Most of the antenna systems are pointed in the opposite direction from the country with which they communicate.

a cylinder rather than a sphere, as relatively little energy is radiated vertically; and in any case the comparison is only intended to indicate that the greater part of the energy is traveling in a direction parallel to the imaginary plane touching the earth at the station. The use of the long wave creates problems of ground and dielectric losses which increase with the wavelength and are produced through direct induction by the stationary waves set up in the antenna system and in surrounding metallic systems, especially if there are any short waves produced in the form of harmonics.

It is more than probable that circuits in which the natural wavelength is many times as long as the greatest mechanical dimension, will be used in handling long waves; this has been done by Alexanderson and others with the multiple-tuned antenna. Most linear objects when oscillating have a wavelength between 2.1 and 2.5 times their dimensions; thus the difference in behavior of these two classes of circuits, used with proper amplifiers for receiving, opens a large field for experimentation.

It has been maintained by French engineers that the possibilities of audio frequency have not yet been realized in connection with "T. P. S.," or what is known as earth telegraphy. Judging from their work in the World War, an antenna ten miles long would give reliable communication under average conditions with another parallel to it—300 miles away overland.

Reasoning along these lines and bearing in mind the much less favorable conditions of transoceanic work, they believe that a ground antenna of about 220 miles in length, situated on the French coast, would provide excellent communication with a similar antenna in the United States.

Such a system is illustrated on page 459. In this system the transmitting and receiving wires should be near the shore and arranged so as to be parallel, with the ends grounded. They would have the same natural frequency as the wave to be transmitted, and undamped waves would be used which could be heard without a detector to rectify them. The ratio of antenna length to range is now more than 50 on land, but would be less over the sea.

It has often been suggested that audio frequency waves be used commercially in "T. P. S." For the average person this would mean a wavelength greater than 30,000 meters, although many engineers can hear LY (the Lafayette station at Bordeaux) on a 6-stage radio frequency amplifier without a heterodyne. The ordinary telephone diaphragm can be made to vibrate at these high rates if the frequency coincides with the natural overtones of the diaphragm.

If audio frequency waves were used the detector tubes themselves might give out a note; the Lafayette station, at 22,100 meters, gives out a frequency of 13,630 cycles or about two octaves above the top note of the piano. The wavelength of this sound in air is about one inch, and one engineer in a testing station at Rockland, Maine, where signals were being measured, could hear these acoustic waves in a room twenty feet from the set.

The advantages of doing away with detectors and audio amplifiers are obvious. If the telephone for transforming sound to electric currents and *vice versa* could be replaced by a device which would have little or no mechanical inertia, the problem of reducing static by acoustic means to a negligible amount would be permanently solved and long distance radio communication at the longer wavelengths would be assured.

The use of such waves would call for the introduction of reliable mechanical relays, and if real rectifiers were combined with them and the heterodyne principle used to produce pulses at 10 to 100 a second, we could actually use tuned relays for recording the messages. This would minimize both static and interference to a large extent.



Underwood & Underwood

BAILING MUSIC FROM THE ETHER WITH A PAIR OF PAILS

A radio fan in Sheffield, England, has found that it is unnecessary to purchase a loop antenna as long as his garden is furnished with two ordinary tin pails. Using them as a literally "home-made" loop, he has had no trouble in picking up music broadcast from Manchester and London.

G. REUTHE.

ANTENNA FOR RADIOTELEGRAPH STATIONS.

APPLICATION FILED APR. 29, 1916.

1,214,591.

Patented Feb. 6, 1917.

3 SHEETS—SHEET 1.

Fig: 1

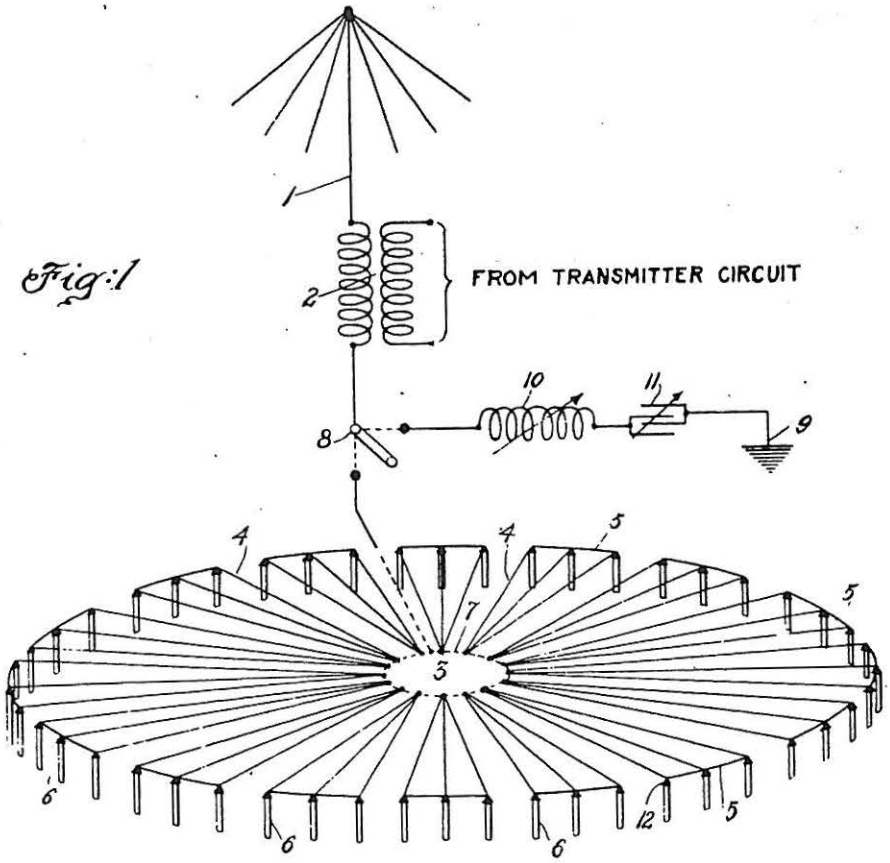
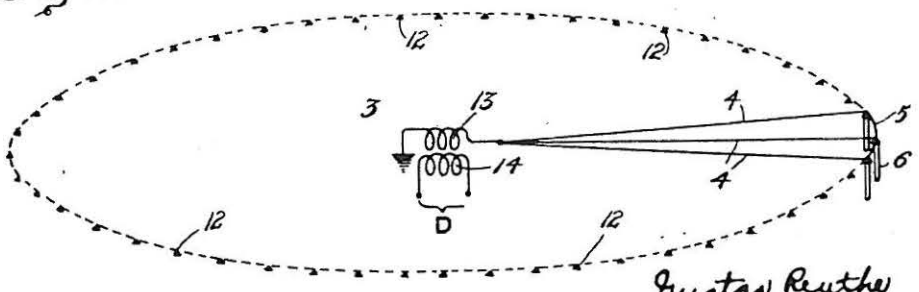


Fig: 2.



Gustav Reuthe
Inventor

By his Attorney

G. REUTHE.

ANTENNA FOR RADIOTELEGRAPH STATIONS.

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3 SHEETS—SHEET 2.

Fig: 6.

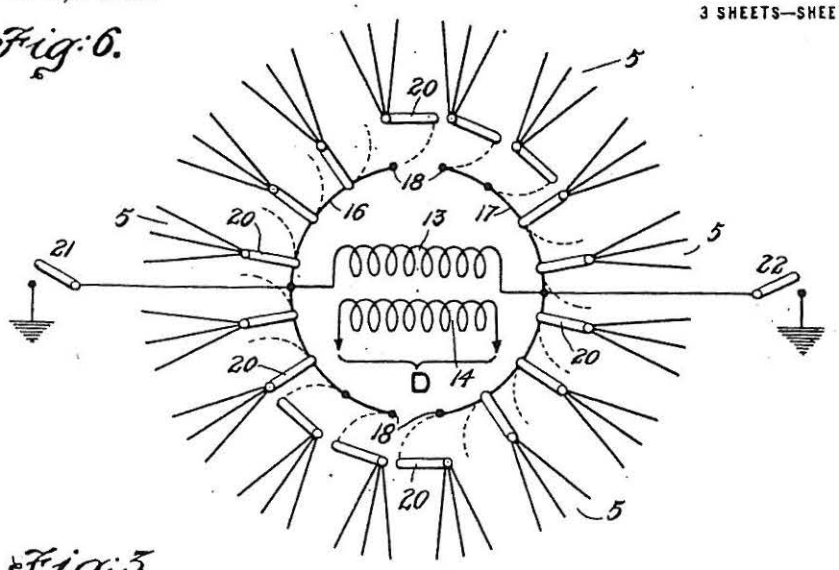


Fig: 3

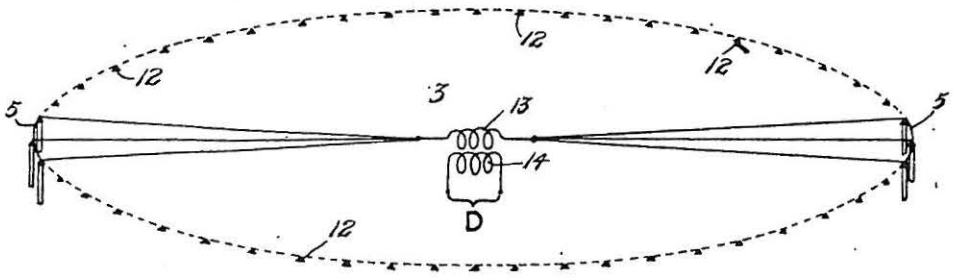


Fig: 4.

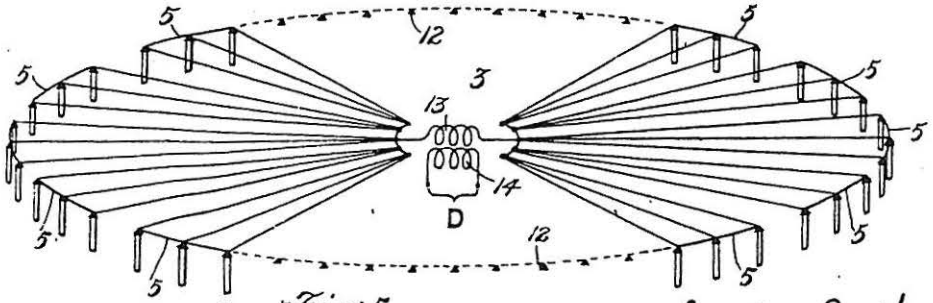
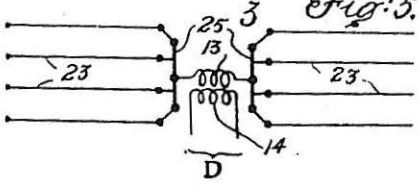


Fig: 5.



Gustav Reuthe
Inventor

By his Attorneys

G. REUTHE.

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3 SHEETS—SHEET 3.

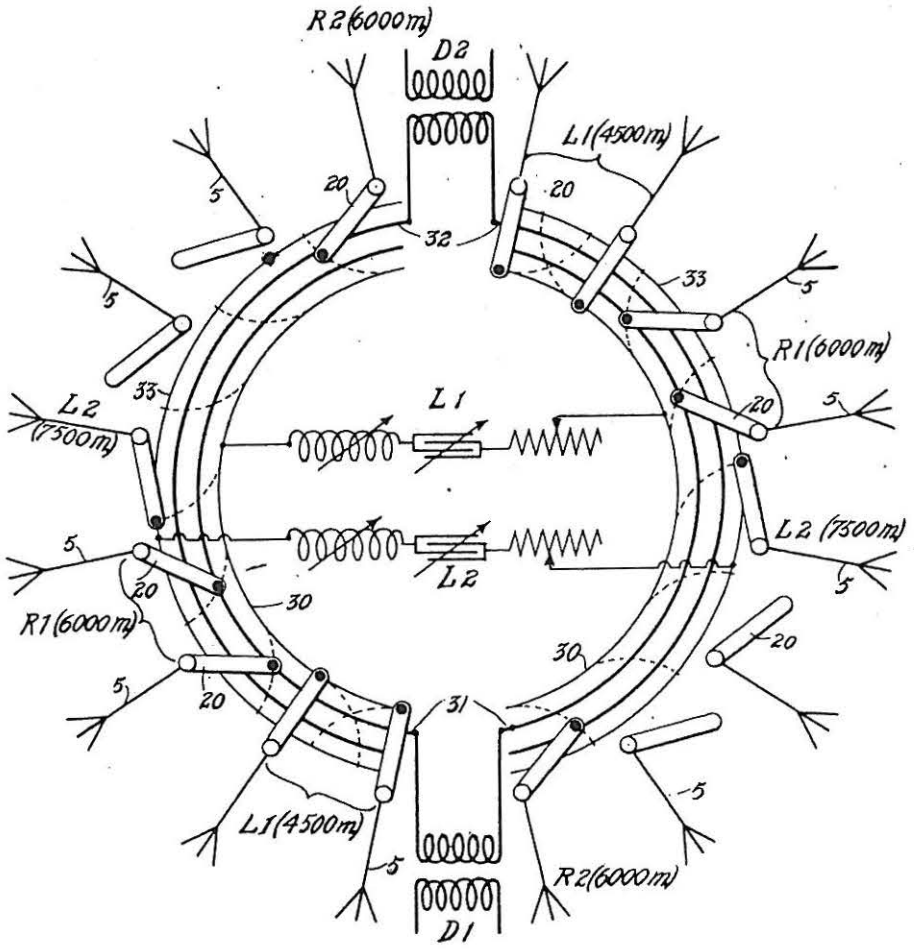


Fig: 7.

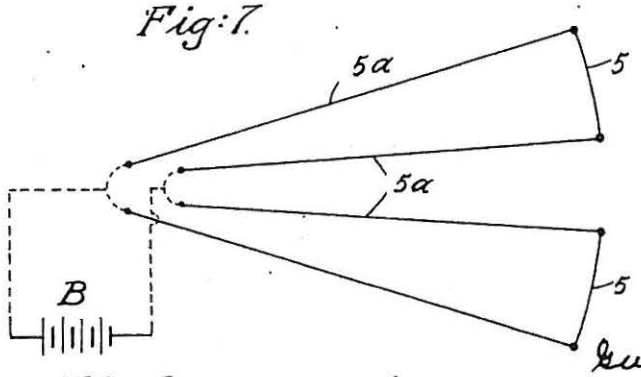


Fig: 8.

Inventor
Gustav Reuthe

By his Attorneys

UNITED STATES PATENT OFFICE.

GUSTAV REUTHE, OF SAYVILLE, NEW YORK, ASSIGNOR TO ATLANTIC COMMUNICATION COMPANY, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK.

ANTENNA FOR RADIOTELEGRAPH-STATIONS.

1,214,591. Specification of Letters Patent. Patented Feb. 6, 1917.

Application filed April 29, 1916. Serial No. 94,351.

To all whom it may concern:

Be it known that I, GUSTAV REUTHE, a subject of the German Emperor, residing at Sayville, county of Suffolk, Long Island, State of New York, have invented certain new and useful Improvements in Antennæ for Radiotelegraph-Stations, of which the following is a full and clear description, illustrated in the accompanying drawings, the novel features of my invention being set forth more particularly in the annexed claims.

It is known that atmospheric disturbances manifesting themselves in the receiving systems of radio telegraph stations can be traced to two different causes.

The first cause is the electro-magnetic effect of electric discharges in the atmosphere at long distance. These discharges by what might be termed "impulse effects," disturb the antenna so as to oscillate with its natural period, which oscillations then in turn manifest themselves in the detector circuit. The effect of such long distance atmospheric discharges is the greater the higher the receiving antenna is and the smaller its damping. For this reason high antennæ (for instance of the umbrella-T- or L-type) which contain a large self induction in circuit and which are particularly suitable for sending, are very unsuited for receiving, whereas on the other hand low horizontal antennæ not suited very well for transmitting on account of their small height above the ground, and on account of their high damping, are very well suited for receiving because they offer great advantages with regard to lessening atmospheric disturbances. The second cause is static charges which the antenna receives through the electric field in the atmosphere. So long as this field and thus the charges which the antenna receives remain constant, they have no effect upon the detector system. They will, however, influence the detector immediately when the electric field in the atmosphere varies. Then currents are induced in the antenna, which similar to distant atmospheric discharges cause the antenna to swing with its own period and thus to disturb the detector system. With regard to these two causes, the combination covered by the U. S. Patent No. 1,082,221 granted to Georg von Arco on December 23rd, 1913, which comprises a comparatively high transmitting antenna and a comparatively low horizontal receiving antenna is particularly favorable, provided however that during receiving the transmitting antenna is detuned against the frequency of the arriving waves. Thus in case of distant atmospheric discharges the oscillations of natural period produced thereby do not affect the horizontal antenna and the detector system coupled therewith, because during receiving the transmitting antenna is detuned against the horizontal antenna and the detector system. The horizontal antenna is very little directly influenced by the atmospheric disturbances because in the first place, such antennæ are very little sensitive against atmospheric disturbances anyhow on account of their small height and their strong damping, and also because a great amount of the energy of the electromagnetic field causing the disturbance is absorbed already by the transmitting antenna. In case of static charges, on the other hand, this combination is particularly favorable because with regard to the electric field in the atmosphere the transmitting antenna has, what may be termed, a "screening action" upon the horizontal antenna below, similarly to the effect produced by Faraday's cage. This screening effect will be the more complete, the larger the area of the transmitting antenna. It will be particularly complete in case the transmitting antenna is of the umbrella or tent type, though of course my invention also covers L- or T- types of antennæ, in which this effect is also present to some extent.

In technically developing this system, it has been proven to be of great advantage to use a transmitting antenna having a counterpoise and to divide the counterpoise into individual sectors which can be separated electrically from each other.

My invention is shown in the annexed drawings, in which,

Figure 1 shows the entire antenna arrangement with the counterpoise; Fig. 2 is a modification showing the counterpoise alone in a form in which one single sector is used for receiving; Fig. 3 is a modification showing a form of the counterpoise

in which two opposite sectors are used for receiving; Fig. 4 is a modification showing several oppositely disposed sectors of the counterpoise joined together for receiving and in order to obtain a different wave length; Fig. 5 is a plan view of a further modification of the counterpoise; Fig. 6 is a detail illustration of the form in which the individual sectors of the counterpoise may be thrown into circuit; Fig. 7 is a modification of Fig. 6; Fig. 8 shows the antenna wires arranged for heating.

Referring now to Fig. 1, 1 is the vertical antenna preferably an umbrella antenna to which the transmitter circuit (not shown here) may be coupled by means of coupling coils 2. 3 is the counterpoise used as a horizontal antenna as will be described hereinafter. It consists of a considerable number of radially extending wires 4 so as to cover an approximately circular area, a suitable number of adjoining wires (in this case, three) being connected into groups so as to form an even number of sectors 5 as shown. The wires of each group are connected together at their outer ends and supported a short distance above ground by posts 6 from which the wires are insulated. For sending, this horizontal antenna is used as the counterpoise for the vertical antenna and in this instance, all its sectors are connected at their inner ends as shown by the dotted line 7 and then connected to the vertical antenna by means of switch 8. For receiving, the vertical antenna is disconnected from the horizontal antenna by a switch 8 and thrown in circuit with a ground connection 9 which may or may not contain an inductance 10 and a capacity 11. If desired, during the receiving the vertical antenna may not be connected to the ground.

During receiving the horizontal antenna 3 may be used in several different ways which are illustrated in Figs. 2 to 4. In all these figures it should be assumed that of course all the radially extending wires 4 are in place though they may not be all connected. The wires are indicated by the black insulators 12 which are mounted on top of posts 6, the posts being omitted in the illustrations. Referring now particularly to Fig. 2, this modification shows the use of only one single sector for receiving. The inner end of the sector is connected to the transformer coil 13, the other end of which is connected to ground. This coil is coupled with the coil 14 which leads to the detector circuit arrangement not shown here, but merely marked with D in Figs. 2–5. The vertical antenna, which is not shown in Fig. 2, being disconnected from the horizontal antenna is of course considerably detuned thereby and if it is connected to the ground at 9 as described before, its detuning may still be materially increased by the capacity 11 and the inductance 10, so that if it is excited by atmospheric disturbances, it will not only not interfere with the receiving by means of the single sector 5 of the low horizontal antenna, but have the screening effect previously referred to. All the remaining sectors of the low horizontal antenna are disconnected from the receiving circuit and from each other.

The modification shown in Fig. 3 in which the vertical antenna (as also in Fig. 4) is assumed to be similarly arranged but not illustrated, shows two oppositely disposed sectors 5 of the low horizontal antenna 3 connected at their inner ends to the respective ends of coupling coil 13 of the receiving arrangement. The remaining sectors are disconnected and the vertical antenna which is also disconnected may be arranged at that time as described before.

In Fig. 4 a number of diametrically, oppositely disposed sectors 5 are connected in groups and these opposite groups are connected to the two opposite ends of the coil 13 of the receiving arrangement. In the case of Figs. 3 and 4, the antenna assumes the form of a symmetrical, low horizontal antenna which in itself in combination with other features is known in the art, for instance in the U. S. Patent No. 979,144, to Fessenden, though the manner in which I apply such a symmetrical antenna is different from the way in which it is employed in the patent above referred to. In particular one of the purposes of the arrangements covered by the present invention, that is to say, to screen during receiving the low horizontal antenna from atmospheric disturbances by a large, high vertical transmitting antenna which is detuned, has not been sought nor accomplished to my knowledge by any of the arrangements of a low horizontal antenna disclosed in the prior art.

In the practical commercial use the antenna arrangements described hereinbefore have the great advantage that it is not necessary to erect a special, low horizontal antenna aside from the counterpoise which is used in electrical connection with the vertical antenna for transmitting, a use of the counterpoise which so far as I am aware, is also new in the art.

Arrangements of the form using the vertical antenna with the counterpoise and a special low horizontal antenna to which the counterpoise can be connected at will, are for instance shown in Patent No. 1,082,221 of December 23rd, 1913, to Georg von Arco, but it should be noted that in none of the forms shown in that patent, the novel combination described hereinbefore is used. In that patent aside from the low horizontal antenna, a special counterpoise is necessary which in case of large stations, for

which my invention is particularly suited, involves considerable expense through the additional wires and causes great inconvenience through the addition of a low horizontal antenna to the counterpoise, which latter naturally should cover as large an area as possible. Moreover, by using the low horizontal antenna in the preferred forms shown in Figs. 2 to 4, where any numbers of sectors may be connected to the receiving arrangement so that any desired compass direction may be covered, the great advantage is obtained that in case of receiving from several differently located stations, those portions of the low horizontal antenna which coincide with the direction of the received waves and by which, as is known, a particularly favorable effect is obtained, may always be connected for receiving. Moreover an arrangement such as I have shown renders it possible to vary the capacity of the low horizontal antenna for receiving in wide limits by using only a few or many sectors as is shown in Figs. 3 and 4, so that the antenna can receive at quite a variety of wave lengths.

In case a station operates principally with only one other station so that the messages are received practically only from one direction at all times, the low horizontal antenna might be given such form, that it extends principally only in two opposite compass directions. This form is shown in Fig. 5, wherein 13 and 14 represents again diagrammatically the receiving circuit to which that antenna is connected. The vertical antenna is disposed similarly as referred to in the remaining figures, but also here omitted from the drawings. In the preferred opposite compass directions a number of parallel wires 23 extend from the receiver, their inner ends being connected to bus bars 25, 25 between which the primary coil 13 of the receiver is connected. As many of the parallel wires 23 as desired may be connected to the bus bars so as to vary the wave length of the low horizontal antenna.

To simplify the connection of the several sectors to the receiving arrangement, as shown in Figs. 2–5, it is of course necessary to provide suitable switches by which this can be accomplished. That this can be done in a number of different ways to suit the particular requirements of the installation is obvious. I have shown in Fig. 6 more or less diagrammatically as an example one way in which this can be accomplished. This figure only shows the central portion of the sectors 5. The receiving coil 13 is connected at each end to the bus bars 16 and 17, these bars being shown in this particular case semi-circular for convenience. These bars have contacts 18, each bar a number equal to one-half of the numbers of sectors which the horizontal antenna contains. For instance, in the modification Fig. 1, the antenna contains 16 sectors so that each bar has 8 contacts. The inner end of each sector terminates in a switch 20 which can be thrown onto its corresponding contact 18 so that this sector is thereby connected to the corresponding bar. Thus any number of sectors may be quickly thrown into or out of circuit and the most suitable group of sectors for receiving may be quickly determined. In order to use this switch arrangement for the form shown in Fig. 2, each bar 16, 17 is provided with a switch 21; 22 respectively by which the respective bar may be grounded as shown. This arrangement can be further modified so as to render the horizontal antenna capable of multiple receiving as well as also capable of protecting by means of some of its sectors, other sectors which may be used at the time for directional receiving. This modification is shown in Fig. 7. In principle of arrangement it is similar to that shown in Fig. 6, except that instead of one circle of bus-bars, four circles of two bars each are concentrically arranged, and the switches 20 are placed so that their points may wipe transversely over all four circles of bars so that they can make contact with any of the circles desired. The showing in Fig. 7 is of course somewhat diagrammatical and it is obvious to anyone skilled in the art that in a station in actual practical use the detail arrangement of the switches and bars may be made somewhat more convenient. In this figure the two heavy marked circles of bars 31 and 32 each comprise two substantially half circles which are connected with the detector circuit D, and D_2 in a manner similar to that shown in Fig. 6 at 13, 14. The two other thin lined circular pairs of bars 30 and 33 are provided for connecting some of the antenna sectors desired with local circuits L_1, L_2, the purpose of which will be explained presently.

So far as the directional receiving by means of two oppositely disposed antenna sectors is concerned, which has been described hereinbefore, I have found that it is possible to simultaneously receive from two different directions, even at the same wave length, with two different receiving circuits. Of course such multiple receiving is most effective when the two directions are substantially at right angles to each other or nearly so because then in case of receiving on the same wave length there will be the least interference. On the other hand it is also possible to simultaneously receive by means of two pairs of oppositely disposed sectors from substantially the same direction at different wave lengths. Of course it naturally follows that also from two different directions simultaneous messages can be received at the same time at different wave

lengths. Now the arrangement shown in Fig. 7 enables me to carry out this multiple receiving. I have assumed in this figure the case where I desire to receive simultaneously at the same wave length from two different directions which are substantially at right angles to each other and I have therefore connected two adjacent oppositely disposed pairs of antenna sectors 5 together by means of their respective switches 20 and thrown them on to the two respective halves of bus-bars 31. This may form receiving circuit R_1 which is connected with the detector circuit D_1. Another oppositely disposed pair of single sectors 5 may be connected by their respective switches 20 to the pair of bars 32 which is connected with the detector circuit D_2. This may form the receiving circuit R_2. The antenna sectors connected to the respective circuits as will be seen are substantially at right angles to each other. Both may be tuned to the wave length of 6,000 m. as indicated.

I found by actual practical experience at a large wireless station that in this way messages can be very conveniently and clearly received simultaneously at the same wave length or of course also at different wave lengths.

In the preamble of the specification I have pointed out that the vertical antenna exerts a "screening action" upon the horizontal antenna. I can now increase this screening action upon the sectors of the horizontal antenna which are used at the time for receiving by a certain arrangement of other sectors of the horizontal antenna, which run substantially in the same direction as those used for receiving, and which are preferably located on either side of the receiving sectors. I connect such "auxiliary" sectors as I may term them into local circuits containing inductance, capacity and resistance, such that two diametrically oppositely disposed sectors located respectively on one side of the receiving antenna sectors are connected to one local circuit tuned to a wave length below that at which signals are received, and diametrically oppositely disposed auxiliary sectors located respectively at the other side of the receiving sectors are connected to another local circuit tuned to a wave length above the one at which signals are received. In Fig. 7, the two auxiliary circuits including the auxiliary sectors are termed L_1 and L_2 and may be located on either side of the receiving antenna R_1. L_1 may be tuned to 4,500 m. and L_2 may be turned to 7,500 m. Thus unless a disturbance arrives at exactly 6,000 m. wave length or closely thereto, its energy is at least partly consummated in the local circuits without detrimental effect upon the receiving sectors. This expedient may be particularly favorable where, during receiving, distant thunder showers occur substantially in the direction from which the signals are received. In such case aside from the vertical antenna the two auxiliary horizontal sectors assist greatly in keeping away the disturbance from the receiving circuit.

From the illustration in Fig. 7 it may also be seen that two adjacent pairs of opposite sectors may be thrown into two different receiving circuits, one tuned to one wave length, the other to another wave length and thus two kinds of signals may be simultaneously received from substantially the same direction.

While it is not shown in Fig. 7 for simplicity's sake, it is of course obvious to anyone skilled in the art that all the pairs of bus-bars may be provided with grounding switches such as are shown at 21 and 22 in Fig. 6 for the purposes referred to in the specification, and it is also obvious to anyone skilled in the art that by the arrangement shown in Fig. 7 a large number of combinations of sectors is possible according to the local conditions and those of receiving.

In cases, where the station is exposed to severe winter weather, especially ice storms, it is advisable to arrange the wires, of which the horizontal antenna sectors are formed, so that each sector or portions of it can be formed into a loop, which can be thrown in circuit with a strong source of alternating or direct current, when the antenna is not used for receiving or sending. Any destructive formation of ice on the wires can thus be easily melted off. An arrangement of the wires of two adjacent sectors is shown in Fig. 8 as an example. The two sections 5—5 are open at their inner ends so that their individual wires 5* may be connected to the battery B or any other suitable source of direct or alternating current in any suitable manner (in series or in parallel) as the occasion and the source of current may require. In Fig. 8 for example a multiple connection of two adjacent sectors is shown in dotted lines. Any other connection will be obvious to anyone skilled in the art. I have found in practice that for such purposes current of considerable intensity is required rather for a short time, than current of smaller intensity for a longer time, on account of the strong heat radiation of the wires. Therefore the division of the horizontal antenna into sectors for radiotelegraphic purposes affords at the same time a very convenient arrangement for thawing off ice coated wires because the individual sectors can be connected successively to the heating circuit, for which considerably less electric energy is required than would be necessary, were the horizontal antenna arranged as one integral net of wires commonly used heretofore. Up to the

present this latter arrangement appears to have stood in the way of successfully thawing off antenna wires.

I claim:

1. In a radio telegraph station the combination of a high vertical antenna for transmitting and a low horizontal antenna for receiving, said vertical antenna being connected electrically during transmission with said horizontal antenna as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving.

2. In a radio telegraph station, the combination of a high vertical antenna for transmitting, and a low horizontal antenna for receiving, having a suitable number of sections, said vertical antenna being connected during transmitting with all of said sections as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving and at least one of its sections being used as a low horizontal antenna for receiving.

3. In a radio telegraph station, the combination of a high vertical antenna for transmitting and a low horizontal antenna for receiving, said vertical antenna being connected electrically during transmitting with said horizontal antenna as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving, and means for detuning the vertical antenna.

4. In a radio telegraph station, the combination of a high vertical antenna for transmitting, and a low horizontal antenna for receiving, having a suitable number of sections, said vertical antenna being connected during transmitting with all of said sections as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving and at least one of its sections being used as a low horizontal antenna for receiving, and means for detuning the vertical antenna.

5. In a radio telegraph station the combination of a high vertical antenna for transmitting and a low horizontal antenna for receiving, said horizontal antenna consisting of a suitable number of radially extending wires forming an approximately circular area and being connected in suitable numbers in individual groups to form independent sectors of the circle, said vertical antenna being connected during transmission with all of said sectors as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving, and at least one of its sectors being used as a low horizontal antenna for receiving.

6. In a radio telegraph station the combination of a high vertical antenna for transmitting and a low horizontal antenna for receiving, said horizontal antenna consisting of a suitable number of radially extending wires forming an approximately circular area and being connected in suitable numbers in individual groups to form independent sectors of the circle, said vertical antenna being connected during transmission with all of said sectors as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving, and at least one of its sectors being used as a low horizontal antenna for receiving, and means for detuning the vertical antenna against the frequency of the arriving waves during receiving.

7. In a radio telegraph station the combination of a high umbrella type antenna for transmitting and a low horizontal antenna for receiving, said horizontal antenna consisting of a suitable number of radially extending wires forming an approximately circular area and being connected in suitable numbers in individual groups to form independent sectors of the circle, said vertical antenna being connected during transmission with all of said sectors as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving, and at least one of its sectors being used as a low horizontal antenna for receiving, and means for detuning the vertical antenna against the frequency of the arriving waves during receiving.

8. In a radio telegraph station the combination of a high vertical antenna for transmission and a low horizontal antenna for receiving, said horizontal antenna consisting of a suitable number of radially extending wires forming an approximately circular area and being connected in suitable numbers in individual groups to form independent sectors of the circle, said vertical antenna being connected during transmission with all of said sectors as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving, and at least one of its sectors being used as a low horizontal antenna for receiving, said vertical antenna having a ground connection and having suitable inductance and capacity in circuit therewith to detune the antenna against the frequency of the arriving waves during receiving.

9. In a radio telegraph station the combination of a high umbrella type antenna for transmitting and a low horizontal antenna for receiving, said horizontal antenna consisting of a suitable number of radially extending wires forming an approximately circular area and being connected in suitable numbers in individual groups to form independent sectors of the circle, said vertical antenna being connected during transmission with all of said sectors as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during re-

ceiving, at least one pair of oppositely disposed sectors being connected as a low horizontal antenna for receiving, and means for detuning the high antenna against the frequency of the arriving waves during receiving.

10. In a radio telegraph station the combination of a high vertical antenna for transmitting and a low horizontal antenna for receiving, said horizontal antenna consisting of a suitable number of radially extending wires forming a circular area and being connected in suitable numbers in individual groups to form independent sectors of the circle, said vertical antenna being connected during transmission with all of said sectors as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving, each of said sectors having a suitable switch connection to permit the combination of any desired number of oppositely disposed sectors to vary the capacity of the low horizontal antenna and to render it directive for receiving, and means for detuning the vertical antenna against the frequency of the arriving waves during receiving.

11. In a radio telegraph station the combination of a high umbrella type antenna for transmitting and a low horizontal antenna consisting of a suitable number of radially extending wires forming an approximately circular area and being connected in suitable numbers in individual groups to form independent sectors of the circle, said vertical antenna being connected during transmission with all of said sectors as a counterpoise, said horizontal antenna being disconnected from the vertical antenna during receiving, at least one pair of oppositely disposed sectors being connected as a low horizontal antenna for receiving, local circuits containing inductance, capacity and resistance, means for connecting the pairs of opposite sectors adjacent to either side of the receiving sectors each to one of said local circuits, said local circuits being tuned respectively to a wave length above and below that of the receiving antenna for screening the receiving antenna from disturbance, and means for detuning the high antenna against the frequency of the arriving waves during receiving.

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ANTENNA.

APPLICATION FILED SEPT. 13, 1917.

1,360,167.

Patented Nov. 23, 1920.

2 SHEETS—SHEET 1.

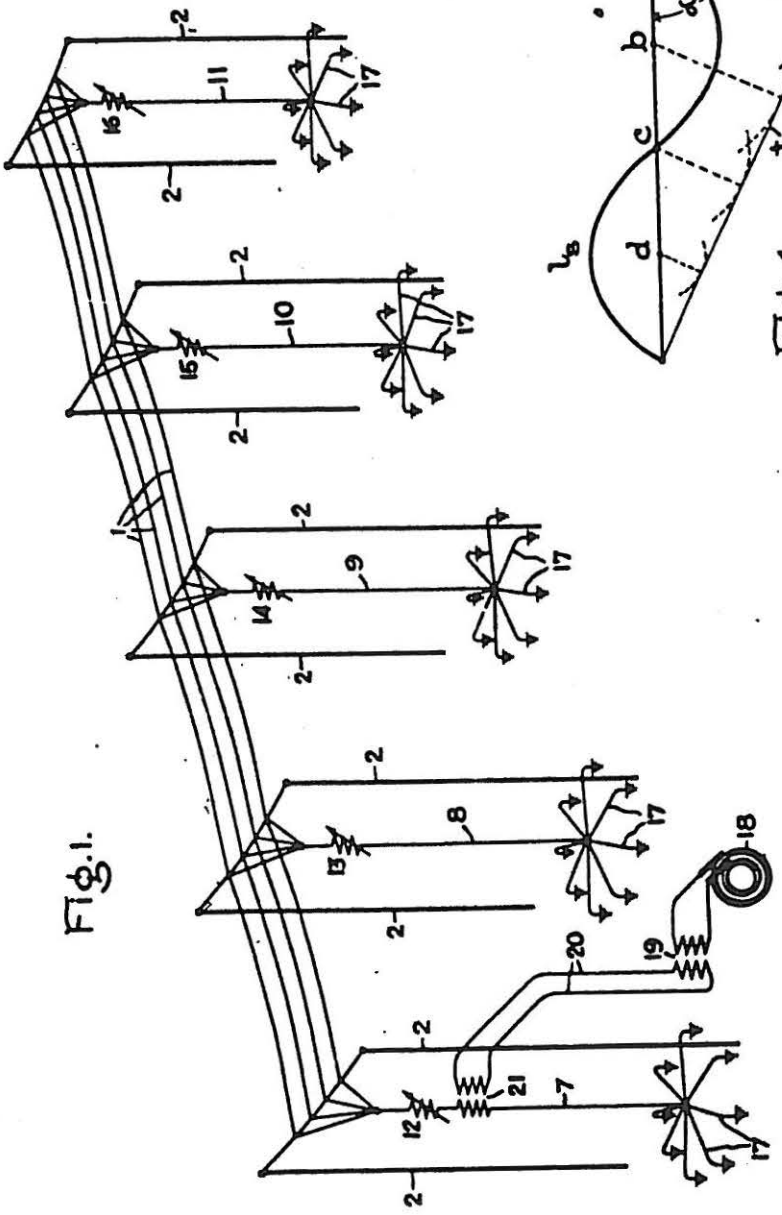


Fig. 1.

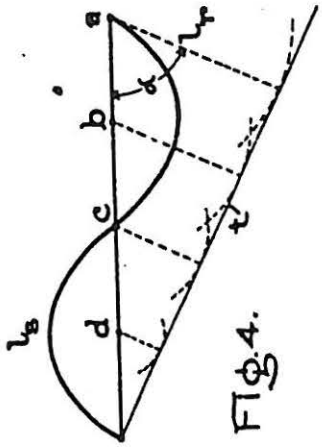


Fig. 4.

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2 SHEETS—SHEET 2.

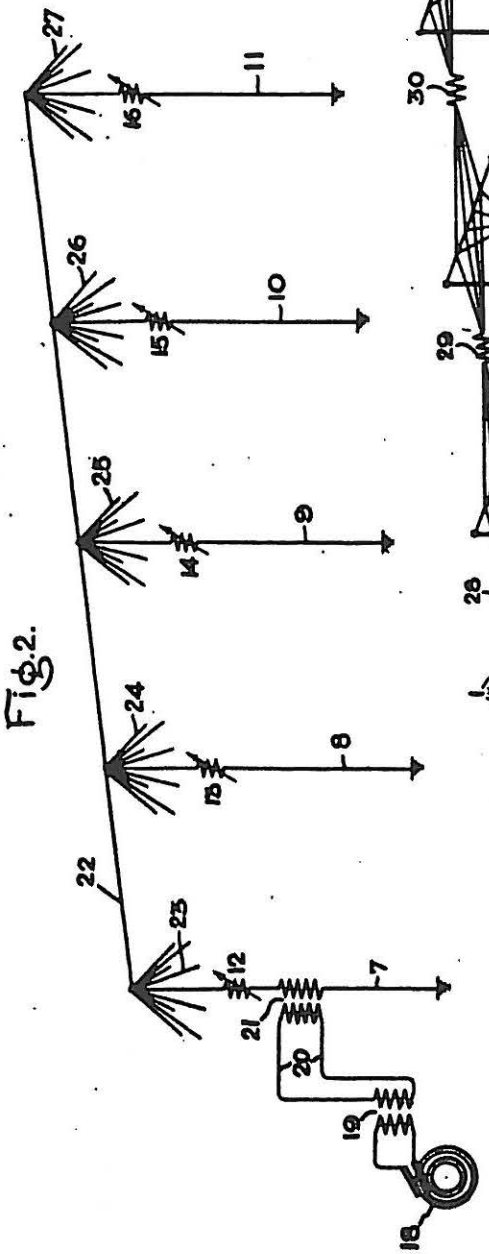


Fig. 2.

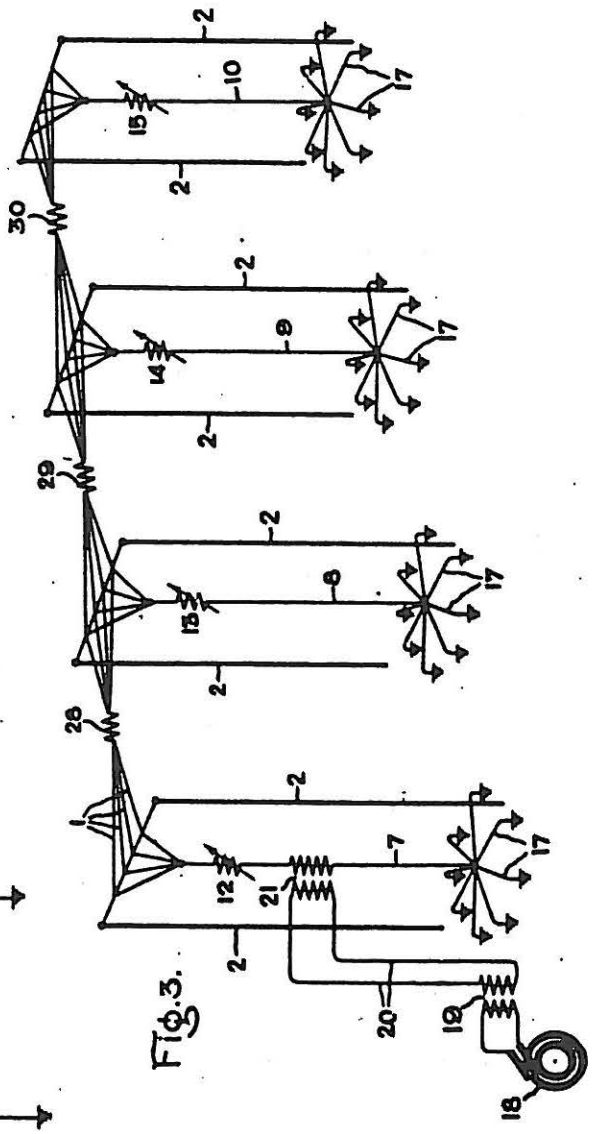


Fig. 3.

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UNITED STATES PATENT OFFICE.

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ANTENNA.

1,360,167. Specification of Letters Patent. Patented Nov. 23, 1920.

Application filed September 13, 1917. Serial No. 191,110.

To all whom it may concern:

Be it known that I, ERNST F. W. ALEXANDERSON, a citizen of the United States, residing at Schenectady, in the county of Schenectady, State of New York, have invented certain new and useful Improvements in Antennæ, of which the following is a specification.

My present invention relates to antennæ for radio signaling systems and more particularly to the manner in which the radiation of the transmitting system is effected. My present application is a continuation in part of my prior application Serial No. 123,276 filed Oct. 2, 1916.

The antenna of a radio signaling system as previously constructed has consisted of an elevated electrical conductor or a net work of conductors which is charged by a source of high frequency energy in such a way that it becomes a source of energy radiation of the type known as the Hertzian oscillator. The theory for the radiation of an antenna has therefore been universally treated by the mathematical theory of the Hertzian oscillator.

The usual radiating antenna system may be considered as a single Hertzian oscillator. It has been proposed heretofore to employ a plurality of such oscillators in order to increase the amount of radiation or to secure directive effects but no practical use has been made of this idea because of the difficulties of controlling the phase of the oscillations in the different radiators in such a way that they would produce a combined radiation of a predetermined desired character.

One of the objects of my invention is to provide means whereby it will be possible to operate a plurality of practically separate radiators in such a way that a combined radiation of the desired character may be readily obtained.

There are several advantages which may be obtained by operating a radiating system as a plurality of separate radiators instead of as a single radiator. One of these advantages is that less energy consumption is required in order to produce a given strength of signals. This advantage may be explained briefly as follows:

In any single radiator, the strength of the electrostatic and the electromagnetic field of the radiated wave is proportional to the current and voltage supplied to the radiator. The energy consumed by the radiator is proportional to the product of current and voltage and is consequently proportional to the square of the field intensity of the radiated wave. The general theory of wave motion, however, teaches that if several systems of waves are superimposed, they combine in such a way that the field intensity in any one place is the algebraic sum of the momentary intensities of all the separate waves. If a system consisting of a plurality of separate radiators is controlled in such a way that the relative phase of the oscillations from the individual radiators is made to combine in a predetermined desired way, it will be possible to operate the system in such a manner that the field intensity in the receiving station is the arithmetic sum of the field intensities produced by all of the individual radiators. A radiation of unity intensity from a station with a single radiator may be said to produce a field intensity of unity in the receiving station. If a system comprising a plurality of radiators is operated in such a way that each of the radiators emits a wave of unity intensity, the effect on the receiving station will be the same as that of a wave with a field strength of as many times unity as there are individual radiators.

The energy consumption of the single radiator may also be called unity and the energy consumption of each of the individual radiators of the multiple system will also be unity when operated as described. If then we assume that there are six individual radiators we will obtain with an energy consumption of six times that of the single radiator a field intensity at the receiving station which is six times as great as that obtained with a single radiator. If it were, on the other hand, desired to produce by a single radiator, a wave at the receiving station having a field strength equal to six times unity it would be necessary to increase the current as well as the voltage in the single radiator to six times unity and consequently the energy consumption of the single radiator would be 36 times unity. Thus it will be seen that the energy consumption of the single radiator will be six times as great as that of the six individual radiators in order to produce the same intensity of signals.

A second advantage of my multiple radiation system is that it renders possible the production of signals of greater intensity than it has been possible to produce heretofore regardless of the amount of energy consumed. With any antenna there is a practical limit to the amount of radiation which may be obtained, this limit being partially fixed by the maximum voltage for which it is practical to insulate the aerial. In other words, it is not possible to increase the strength of the signal above a certain value by increasing the amount of energy supplied to a single radiator, whereas with a plurality of individual radiators any increase in the signal strength desired may be obtained merely by increasing the number of radiators.

A third advantage of my system of multiple radiation is that it renders possible the production of a radiation of energy with a decided directive effect comparable with the focusing of a beam of light by a lens or a mirror. While the desirability of such an effect has frequently been mentioned and various means have been proposed for securing it none of the means heretofore proposed have been found to be applicable to practical operation.

A second object of my invention is to provide a convenient and practical means for adjusting the phase relations of the individual radiations so that the advantages of directive radiation may be realized.

In the usual type of antenna corresponding to a single Hertzian oscillator which has heretofore been used the energy is introduced through a ground lead in series with a loading coil. In an antenna of this type designed for long distance transmission assume that the current introduced through the loading coil is 100 amperes and the potential of the aerial is 50,000 volts. The energy required to maintain oscillations in such an antenna may be 50 kilowatts. This means that the energy component of the oscillating voltage is 500 volts, or as it is commonly expressed, the antenna has a resistance of 5 ohms. Thus the energy required for maintaining oscillations is delivered in the form of 100 amperes at 500 volts. While it might be possible to supply energy to each one of a plurality of radiators in this way such a method would, if the individual radiators were located at a considerable distance from each other, involve unnecessary losses due to inductive or resistance drop in the feeding wires.

A further object of my invention is to provide a system for supplying energy to the individual radiators which will overcome this disadvantage.

In attaining this object of my invention I transform the energy to the form of high potential and low current and instead of supplying it at the ground point of the loading coil supply it at a high tension point. For example, in the case above mentioned, the energy may be supplied to the radiators at 50,000 volts and one ampere. Thus while in each case 50 kilowatts of energy is required the old form of antenna consumes this energy in the same form as if it were a resistance of five ohms whereas the radiator supplied in accordance with my invention consumes the energy in the form of a resistance of 50,000 ohms. This may be explained by reason of the fact that in the old form of antenna the energy is introduced in series with the inductance and capacity of the antenna whereas in the form of a radiator which I employ the energy is introduced to a circuit which is the equivalent of the antenna capacity in parallel with the inductance. By introducing the energy to the individual radiators in this way it is possible to feed a large number of such radiators located at a considerable distance from each other without incurring any great losses in the transmission conductors. In order to transform the energy into the desired form it might be possible to use a transformer of the ordinary type with the required ratio of transformation. I have found, however, that it is more convenient to use one of the radiating circuits as an oscillation transformer, and to supply the energy to all of the other radiators from the high tension end of the first radiator. In its preferred form then, my multiple radiating system may be considered as being made up of a primary radiator which at the same time serves as an oscillation transformer for supplying high tension energy to one or more secondary radiators. In order to have a completely balanced system of radiation, it might appear desirable to locate the primary radiator in such a way relative to the secondary radiators that the energy connections to each of the secondary radiators can be made directly to the primary radiator through wires of equal length. While this might be a practical method of construction, I have found in actual practice that it is not necessary to connect each of the secondary radiators directly to the primary radiator and that it is of practical convenience in the construction of the antenna to connect the secondary radiators successively to each other, that is so that energy current flowing from the primary radiator reaches the secondary radiators in succession. In one case in which my invention has been applied in practice the antenna has the character of a horizontal transmission line supported on towers. This antenna is divided into a plurality of individual radiators by means of ground connections with loading coils therein at suitable intervals along its length. The aerial

wires which serve as radiators also serve for transmitting energy to all of the successive radiators. Since the energy is transmitted to the secondary radiators in the form of high potential and low current it is apparent that a large number of radiators may be connected to such a transmission line without causing any appreciable changes in voltage and phase.

The novel features which I believe to be characteristic of my invention are set forth with particularity in the appended claims. My invention itself however, both as to its organization and method of operation together with further objects and advantages thereof will best be understood by reference to the following description taken in connection with the accompanying drawing in which Figures 1, 2 and 3 show diagrammatically as many different modifications and Fig. 4 is a diagram explanatory of the directive radiation feature of my invention. In the form of my invention indicated in Fig. 1 the radiating system is composed of a plurality of horizontal conductors 1 of considerable length elevated above ground by means of the supports 2 from which they are insulated. This system is divided into five individual radiators by means of the ground connections 7, 8, 9, 10, and 11, individual tuning or loading coils 12, 13, 14, 15, and 16 being included in each ground connection. The ground connections indicated consist of a plurality of wires 17 stretched over the surface of the ground, the end of each conductor being permanently earthed. The energy for signaling purposes is supplied to the first radiator of the series by a high frequency alternator 18, connected through the transformer 19 to a transmission line 20 which conveys the current to the transformer 21 by means of which it is introduced into ground connection 7.

The first radiator comprises the ground connection 7 and the portions of the conductors 1 adjacent thereto and this radiator serves as an oscillation transformer to step up the voltage applied through transformer 21. Energy is thereby supplied directly at a high potential from the first radiator to the second radiator, which comprises the ground connection 8 and the portions of the conductors 1 adjacent thereto. The second radiator also acts as an oscillation transformer changing the high potential low current energy into the form of lower potential larger current producing an oscillating charging current in ground connection 8 which may be of the same magnitude as the charging current in ground connection 7. The conductors 1 also serve as a transmission line for conveying the high potential energy to the third, fourth and fifth radiators in succession. These radiators function in the same manner as the second radiator so that charging currents of the same order of magnitude are set up in all of the ground connections. As an indication of the advantage which may be obtained by the use of my invention tests have been made with an antenna of the type shown in Fig. 1 which was divided up into 6 individual radiators. When 50 kilowatts of high frequency energy were supplied to the antenna and a single ground connection used a charging current of about 100 amperes was obtained. When six ground connections were used the charging current in each ground connection was about 45 amperes making a total charging current of 270 amperes. In other words the effective radiation with the same amount of energy was about 2.7 times that which was obtained when the antenna was operated as a single radiator.

In accordance with the Hertzian theory of radiation the ability of a certain aerial to radiate is determined by the so-called radiation resistance. This radiation resistance is proportional to the square of the ratio between height and wave length. It is also well known that an antenna to be used efficiently should be operated at a somewhat lower frequency than its natural periodicity. This method of operation calls for a certain amount of inductance which is ordinarily used for tuning. If it is attempted to operate the antenna at a higher frequency than the natural periodicity it is necessary to introduce a capacity instead of an inductance for loading and it is known that the operation in this way is inefficient. For long distance working antennæ of large horizontal dimensions are employed. The large horizontal dimensions give high electrostatic capacity and consequently the natural periodicity of the antenna which is determined by the physical dimensions of the aerial is low. Thus if such an antenna is operated at its natural periodicity, or at a lower frequency the wave length is much greater than the height and consequently the ratio between height and wave length results in a low radiation resistance and a high ratio between the radiation resistance and the ground resistance: in other words, in low efficiency. The value to which the ground resistance may be reduced is also limited to a certain extent in practice by the physical dimensions of the antenna. Hence it may be said that such an antenna when used as a simple Hertzian oscillator has a definite maximum possible efficiency or natural ratio between radiation resistance and ground resistance. When, however, the antenna is provided with a plurality of ground connections in accordance with my invention, its natural periodicity is increased beyond the value determined by its physical dimensions when used as a simple Hertzian oscillator,

that is, the natural periodicity of the entire antenna is equal to the natural periodicity of each individual section which is supplied with a ground connection, assuming that the natural periodicity of all of the sections is the same. In other words, the natural periodicity of the antenna is increased to a value much greater than the value which is determined by its physical dimensions. As a result the antenna can be operated efficiently at much shorter wave lengths thereby increasing the radiation resistance inversely with the square of the wave length. The result of this is a more favorable ratio between radiation resistance and ground resistance, since the effect of providing a plurality of ground connections is to decrease the ground resistance; that is, the ratio between radiation resistance and ground resistance or efficiency of the antenna may be greatly increased.

The form of my invention illustrated in Fig. 2 differs from that shown in Fig. 1 merely in its constructional details. In this case each individual radiator takes the form of an umbrella type of antenna and the individual radiators are all connected by a transmission line 22 which supplies high potential energy from the first radiator 23 to the secondary radiators 24, 25, 26 and 27 in succession. A radiating system constructed in this way operates in the same manner as the one illustrated in Fig. 1.

In Fig. 3 I have indicated a modification of my invention which may be employed when it is desired to obtain a directive effect. In this case the individual radiators are separated by inductances 28, 29 and 30 which may be made of such a value as to give the phase displacement in the waves radiated by successive radiators, required to secure the desired directive effect. If desired, condensers may be employed between the individual radiators instead of inductances.

In determining a method whereby a system comprising a plurality of individual radiators may be adapted for directive radiation an antenna such as illustrated in Figs. 1 or 2 may be considered as a uniformly distributed capacity between a linear conductor and ground. The electrostatic field surrounding the conductor extends in three directions but for the purpose of this discussion it will be sufficient to consider the potential gradient only in two directions, that is in the vertical direction between conductor and ground and in the horizontal direction along the conductor. When an aerial conductor is set into oscillation by a source of continuous waves of definite frequency standing waves are formed in the electrostatic field. These waves must be analyzed in accordance with the horizontal as well as the vertical distribution of potential. If the conductor is not connected to ground in any way it has a natural period of horizontal oscillations. In this case no oscillations will occur in the vertical plane. If one end of the conductor is connected to ground it will have another natural period. The oscillations in this case will be horizontal and also to some extent vertical inasmuch as a charging current will pass between the conductor and ground. An aerial conductor thus arranged with the ground connection at one end has previously been used to considerable extent. If such a conductor is connected to ground through a large number of uniformly distributed coils it becomes a multiple radiating antenna as described previously. Furthermore, if the inductance of these coils is so adjusted that the oscillations in all of the different coils are substantially in phase the antenna may be said to have vertical oscillations but no horizontal oscillations. It is, however, possible to tune the antenna in such a way that it has both vertical and horizontal oscillations simultaneously. The vertical and horizontal oscillations may be of different frequency if a source of energy supply of more than one frequency is available. This might be the case if the antenna was excited by an arc generator or a pliotron oscillator. In the present case, however, it will be most convenient to consider the radiation as of a single frequency such as may occur if the antenna is excited by a high frequency alternator, in which case the horizontal and vertical oscillations that take place simultaneously are necessarily of the same frequency. In the case where the conductor is connected to ground at one end only the horizontal oscillations occur in such a way that the grounded end is a node and the open end has maximum amplitude. It was at one time considered that an antenna of this type would produce a directive radiation. It has now, however, been proved that this is not the case, the reason being that the length of the antenna has been less than one-fourth of the wave length of radiation at which it has been operated, whereas to secure an effective directive radiation it would be necessary that the length of the antenna should be at least equal to one-half of the wave length of radiation. In a simple horizontal antenna such as has been described the distribution of capacity and inductance has always been found to be such that the wave length of the standing wave along the antenna is shorter than the wave length of radiation. This condition, as will be explained more fully hereafter, prevents the securing of the most effective radiation. The fundamental rule which should be followed and which will be explained in the following discussion is that the wave length of the standing wave should be equal to or

greater than the wave length of radiation. If radiation is desired in the longitudinal direction of the antenna the standing wave should have a length equal to the wave length of radiation, whereas if a directive radiation is desired at right angles to the direction of the antenna the length of the standing wave should be infinity. For any intermediate angle the relative length of the standing wave and the radiation wave should be equal to the secant of the angle between the direction of radiation and the direction of the antenna. In order to prove this relation geometrically, assume that a wave begins to travel with the velocity of light from one end of the antenna. It is desirable in order to secure maximum efficiency of radiation that the wave as it travels along the antenna should always receive impulses which are in phase with the wave itself. For this reason the standing wave should have a wave length equal to the wave length of the traveling wave. If an antenna oscillates with a standing wave which has a greater wave length than the wave length of radiation, that is, if the wave travels along the antenna at a velocity greater than that of light, the different points of the antenna may be assumed to emit radiation of different phases and the locus for points at which individual waves are of a certain phase may be represented by circles drawn around the different centers of radiation.

Referring now to Fig. 4, assume that the standing wave is represented by l_s. Around point a of the standing wave which is represented as a node a circle may be drawn having a radius equal to the wave length of radiation l_r. Around point b a circle may be drawn of a radius one-quarter of a wave length shorter. Around point c the circle has a radius of one-half a wave length and around point d a radius of one-quarter of a wave length. The line t which is tangent to all of these circles indicates the direction of radiation, the radiation being greatest in a direction perpendicular to this tangent, and it will be apparent from an inspection of this figure that $l_r = l_s \cos \alpha$ where α is the angle between the direction of the antenna and the direction of radiation. Applying the above formula to a case where the standing horizontal wave is shorter than the wave length of radiation the direction of such radiation would be expressed by a cosine greater than unity. This condition being impossible means that no directive radiation can take place and that the radiation will be inefficient.

The type of horizontal antenna connected to ground at one end which has previously been used as such distribution of inductance and capacity that the standing wave is theoretically equal to but in practice has been shorter than the wave length of radiation. In other words, the wave travels along the antenna at a velocity less than the velocity of light. If it is desired to increase the velocity at which the wave travels along the antenna and thereby lengthen the standing wave either the inductance or capacity must be decreased. Anything however which is done in this direction by changing the combination of the wires will defeat the object sought. An additional parallel wire will decrease the inductance but increase the capacity and fewer parallel wires will decrease the capacity but increase the inductance. By the use of a plurality of radiators such as I have described the desired object may be attained. The capacity between the aerial and ground may be neutralized by distributed inductance between the aerial and ground. If the distributed capacity is entirely neutralized by distributed inductance for the frequency at which the antenna is excited the standing wave will have a length equal to infinity, which means that all parts of the aerial conductor will oscillate in phase. This condition produces non-directive radiation if the antenna is shorter than half of the wave length of radiation and directive radiation at right angles to the antenna if the antenna is sufficiently long in relation to the wave length of radiation. If a long antenna is used and directive radiation is desired at any angle except a right angle, the necessary length for the standing wave may be determined from the wave length of the radiation and the desired angle. The inductance of the aerial being known it will then be possible to calculate the amount of distributed capacity which will create a standing wave of the desired length. This required capacity will be found to be lower than the capacity between the aerial and ground. The method to be followed then will be to neutralize the portion of the capacity to ground which is not desired, leaving a balance of distributed capacity which will give a standing wave of the desired length. Instead of neutralizing the capacity to ground it will be possible to neutralize the longitudinal inductance of the aerial conductor by series condensers. Both of these methods may be used in combination if desired.

If the method of adjusting the tuning of the antenna is considered from the above point of view it will be found that the method of radiation which consists in using a number of independent radiators excited from a common source of high frequency energy in such a way as to operate in phase is only a specific case of a composite horizontal antenna with a horizontal standing wave. This specific case is one where the length of the standing wave is infinity and this method of radiation whether directive or nondirective may be differentiated from

the methods of radiation that have been proposed heretofore by the characteristic that the standing wave has a length equal to or greater than the wave length of radiation, whereas such antennæ as have been used previously have had standing waves of a wave length shorter than the wave length of radiation. The term "standing wave" as used in the above description and in the claims which follow is not employed in the restricted sense in which it is commonly understood, namely, as the resultant of two waves traveling with equal velocity in opposite directions so as to produce points of large amplitude and intermediate nodes of zero amplitude. The phenomenon described by this term is also of a different nature than that known as a "traveling wave" since the latter term as ordinarily used implies a complete transfer of energy from one point to another at the same rate that the wave travels. While in the present case energy is transferred from one point to another this transfer is merely incidental as a large portion of the energy remains fixed in position. Moreover, such transfer as does occur may take place in the opposite direction to the traveling wave effect. At any point along the length of the antenna the amplitude of oscillations is the same as at any other point, but when the standing wave, as the term is here used, is of finite length the oscillations of different portions of the antenna are displaced in phase. The maxima of successive portions occur in succession, however, so that the effect, so far as the wave in the ether is concerned, is that of a traveling wave.

While I have illustrated and described the preferred form of my invention, it will be apparent that many modifications therein may be made without departing from the scope of the appended claims.

What I claim as new and desire to secure by Letters Patent of the United States, is:

1. A radiating antenna system comprising a primary radiating unit supplied by a source of radio-frequency current and a plurality of secondary radiating units an individual ground connection for each of said radiating units, the secondary radiating units being connected successively to a transmission line which supplies energy from the primary radiating unit to the secondary radiating units.

2. A radiating antenna system comprising a primary radiating unit and a plurality of secondary radiating units connected successively together and to the primary unit, an individual ground connection for each of said radiating units, a source of high frequency current connected to the primary unit, the primary radiating unit being directly connected to the first of said secondary units and serving as an oscillation transformer for supplying energy successively to all of the secondary radiating units at a high potential.

3. A radiating antenna system comprising a set of horizontal aerial wires, a plurality of inductance coils connected between said aerial wires and ground at substantially uniformly distributed points along the length of said wires and a source of radio frequency current for supplying energy to the aerial wires at one point, the energy thus supplied being distributed through the aerial wires to maintain synchronous oscillations in each of the oscillating circuits formed by one of said inductances, and the capacity to ground of the portions of the aerial wires adjacent thereto.

4. A radiating antenna system comprising a plurality of sections, all of the different sections being joined together successively by aerial wires, each section consisting of aerial wires connected to ground through an inductance and forming a separate oscillating circuit, and a source of radio frequency current for supplying energy to the aerial wires which join the several sections, each oscillating circuit being tuned to the frequency of the energy thus supplied.

5. The method of supplying energy to a radiating system comprising a plurality of radiating units which consists in supplying energy to one of said units at a comparatively low potential, utilizing said unit as an oscillation transformer for producing a comparatively high potential and distributing energy at the high potential thus produced from the first unit successively to all of the other units.

6. The method of maintaining synchronous oscillations in a plurality of radiating units which consists in supplying radio frequency energy directly to one of said units and supplying energy from said first unit successively to all of the other radiating units.

7. The method of radiating electromagnetic energy from a system of horizontal conductors which consists in producing an electrostatic field in said conductors which has a horizontal standing wave formed therein having a wave length which is at least as great as the wave length which is to be radiated.

8. The method of radiating electromagnetic energy from a radiating antenna system which consists in producing by a single source of radio frequency energy an electrostatic field in said radiating system which has a horizontal standing wave formed therein having a wave length which is at least as great as the wave length which is to be radiated.

9. A radiating antenna system comprising a set of aerial conductors, means for exciting said conductors by a single source of radio

frequency energy, and means for neutralizing, by resonance, the distributed capacity between the aerial conductors and ground, the conductors being so arranged and said means being so adjusted as to produce a standing wave of potential along the aerial conductor having a wave length at least as great as the wave length to be radiated.

10. A radiating antenna system comprising aerial conductors arranged in a horizontal line, a single source of radio frequency current for exciting said antenna system, a plurality of inductances distributed along said aerial conductors and connected between said conductors and ground, said conductors being so arranged and said inductances being adjusted so as to partly neutralize the distributed capacity between the aerial conductor and ground in such a way that the distribution of potential along the aerial conductors will form a standing wave of a wave length at least as great as the wave length to be radiated.

11. The method of radiating electromagnetic energy which consists in charging an insulated continuous system of aerial conductors through a plurality of vertical grounded conductors connected thereto in multiple, the oscillating charging currents in the different ground conductors being regulated so as to have a progressive phase displacement.

12. The method of radiating electromagnetic energy which consists in charging an insulated continuous system of aerial conductors through a plurality of vertical grounded conductors connected thereto in multiple, the oscillating charging currents in the different ground conductors being regulated so that they are progressively shifted in phase to such a degree as to give a directive radiation in a desired direction.

13. The method of radiating electromagnetic energy from a radiating antenna system which consists in neutralizing distributed capacity between said system and ground at a plurality of points in the system, exciting said system by a single source of radio frequency energy, and producing a standing wave of potential along the system having a wave length at least as great as the wave length to be radiated.

14. The method of creating an electromagnetic wave with a directive radiation in a system of aerial wires having a plurality of inductance coils connected between said aerial wires and ground at substantially uniformly distributed points along said wires which consists in producing synchronous oscillating currents in all of the ground conductors by means of energy introduced into the system through one ground conductor and regulating the currents in the different conductors so that they will have a progressive phase displacement.

15. The method of directive signaling which consists in supplying energy from a source of radio frequency current to a radiating unit, supplying energy from said radiating unit to a plurality of other radiating units and adjusting the relative phases of the currents in the different radiating units so that the waves emitted by all of the units add accumulatively at points in a certain predetermined direction.

16. The method of directive signaling by means of electromagnetic waves which consists in supplying energy from a source of radio frequency current to a radiating unit and supplying energy from said radiating unit to a plurality of other radiating units which are so adjusted that the interference effect of the waves emitted therefrom creates a maximum amplitude of signal in a desired direction and a minimum amplitude in another direction.

17. The combination in a radio signaling system of an insulated system of aerial conductors, a plurality of vertical conductors each of which has one end connected to said aerial system and the other end grounded, means for supplying energy to the entire system through one of said vertical conductors to produce synchronous oscillating currents in all of the vertical conductors, and means for adjusting the phase relation of the currents in the different vertical conductors in such a way as to produce a directive radiation.

18. The combination in a radio signaling system of an insulated system of aerial conductors, a plurality of vertical conductors each of which has one end connected to said aerial system and the other end grounded, means for supplying energy to the entire system through one of said vertical conductors to produce synchronous oscillating currents in all of the vertical conductors and means for adjusting the relative phases of the different oscillating currents so that the waves produced by these currents add accumulatively at points in a certain predetermined direction.

19. The combination in a radio signaling system of an insulated system of aerial conductors, a plurality of vertical conductors each of which has one end connected to said aerial system and the other end grounded, means for supplying energy to the entire system through one of said vertical conductors to produce synchronous oscillating currents in all of the vertical conductors and means for adjusting the relative phases of the different oscillating currents so that the interference effect of the waves produced creates a maximum amplitude of signal in a desired direction and a minimum amplitude in another direction.

20. A radiating antenna system comprising a continuous system of aerial conductors

arranged in a horizontal line, a plurality of ground connections for said system containing tuning means located at substantially uniformly distributed points along the length of said system whereby said system is divided into a plurality of radiating units capable of oscillating substantially independent of one another, and means for supplying energy to said system through a single one of said ground connections.

21. A radiating antenna system comprising a system of continuous elevated horizontal conductors, a plurality of ground connections for said system containing tuning means located at substantially uniformly distributed points along the length of said system whereby said system is divided into a plurality of radiating units capable of oscillating substantially independent of one another, and means for supplying energy to said system through the ground connection nearest one end whereby said elevated conductors serve both as a plurality of substantially independent radiating units, and to transmit energy at a high potential from the first radiator to the other radiators in succession.

22. An antenna for a wireless signaling system comprising a long horizontal continuous conducting network supported above the earth and connections between said network and earth at a plurality of successive points along its length whereby the natural periodicity of the antenna is increased beyond the value determined by its physical dimensions when used as a simple Hertzian oscillator, all of said earth connections including inductances adjusted in such a way that the multiple impedance of the inductances is equal to that of a single inductance necessary for tuning the whole antenna at the operating frequency.

23. The combination in a wireless signaling system of an antenna comprising a long horizontal conducting network supported above the earth and connections between the said network and earth at a plurality of successive points whereby the natural periodicity of the antenna is increased beyond the value determined by its physical dimensions when used as a simple Hertzian oscillator, all of said earth connections including inductances, and means for supplying the energy necessary for maintaining oscillations of a single definite frequency in the entire system through one of the multiple paths to ground.

24. The combination in a wireless signaling system of an insulated system of long horizontal continuous aerial conductors, a plurality of successive vertical conductors each of which has one end connected to said aerial system and the other end grounded, and a source of sustained high frequency oscillations for producing synchronous oscillating currents of a single definite frequency in a plurality of multiple paths, each of which comprises a vertical conductor and the space capacity of a portion of the aerial.

25. The combination in a wireless signaling system of an insulated system of long horizontal continuous aerial conductors, a plurality of vertical conductors each of which has one end connected to said aerial system and the other end grounded, and a source of sustained high frequency oscillations for producing substantially in phase oscillating currents of a single definite frequency in all of the vertical conductors.

26. The combination in a wireless signaling system of an insulated system of long horizontal continuous aerial conductors, a plurality of vertical conductors each of which has one end connected to said aerial system and the other end grounded, and a source of sustained high frequency oscillations for producing oscillating currents of a single definite frequency in all of the vertical conductors which differ in phase from one another by less than 90°.

27. An antenna for a wireless signaling system comprising a long horizontal continuous conducting network supported above the earth and having of itself a low natural periodicity and connections between said network and earth at a plurality of successive points along its length, whereby its natural periodicity is increased to a much greater value, all of said earth connections including inductances for tuning said antenna.

28. The combination in a wireless signaling system of an insulated system of continuous aerial conductors, a plurality of vertical conductors each of which has one end connected to said continuous aerial system and the other end grounded, means for producing synchronous oscillating currents in all of the vertical conductors, and means for adjusting the phase relation of the currents in the different vertical conductors in such a way as to produce a directive radiation.

29. The combination in a wireless signaling system of an insulated system of continuous aerial conductors, a plurality of vertical conductors each of which has one end connected to said continuous aerial system and the other end grounded, means for producing synchronous oscillating currents in all of the vertical conductors, and means for adjusting the relative phases of the different oscillating currents so that the waves produced by these currents add accumulatively at points in a certain predetermined direction.

30. The combination in a wireless signaling system of an insulated system of continuous aerial conductors, a plurality of vertical conductors each of which has one end

connected to said continuous aerial system and the other end grounded, means for producing synchronous oscillating currents in all of the vertical conductors, and means for adjusting the relative phases of the different oscillating currents so that the interference effect of the waves produced creates a maximum amplitude in a desired direction and a minimum amplitude in another direction.

31. An antenna for a wireless signaling system comprising a long horizontal conductor insulated from the earth and having such natural constants that an electrical wave will travel along its length at a velocity less than the velocity of light, and means uniformly distributed along the length of said conductor for increasing the velocity at which an electrical wave will travel along the conductor.

32. An antenna for a wireless signaling system comprising a long horizontal conductor insulated from the earth and having such natural constants that an electrical wave will travel along its length at a velocity less than the velocity of light, and means uniformly distributed along the length of said conductor for increasing the velocity at which an electrical wave will travel along the conductor to a velocity at least equal to the velocity of light.

33. An antenna for a wireless signaling system comprising a long horizontal conductor insulated from earth and having such natural constants that an electrical wave will travel along its length at a velocity less than the velocity of light, and a plurality of inductances uniformly distributed along the length of the conductor and connected between the conductor and earth for neutralizing a portion at least of the shunt capacity thereof and thereby increasing the velocity at which an electrical wave will travel along the conductor.

34. An antenna for a wireless signaling system comprising a long horizontal conductor insulated from earth and having such natural constants that an electrical wave will travel along its length at a velocity less than the velocity of light, and a plurality of inductances uniformly distributed along the length of the conductor and connected between the conductor and earth for neutralizing a portion at least of the shunt capacity thereof and thereby increasing the velocity at which an electrical wave will travel along the conductor to a velocity at least equal to the velocity of light.

35. An antenna for a wireless signaling system comprising a long horizontal conductor insulated from earth and having such natural constants that an electrical wave will travel along its length at a velocity less than the velocity of light, a plurality of inductances uniformly distributed along the length of the conductor and connected between the conductor and earth for neutralizing a portion at least of the shunt capacity thereof, and thereby increasing the velocity of the electrical wave in the conductor, and a plurality of inductances connected in series with said conductor between the different earth points for decreasing the velocity of the electrical waves in the conductor to a desired value.

In witness whereof, I have hereunto set my hand this 11th day of September, 1917.

ERNST F. W. ALEXANDERSON.

E. F. W. ALEXANDERSON.

ANTENNA.

APPLICATION FILED FEB. 15, 1918.

1,360,168. Patented Nov. 23, 1920.

Fig. 1.

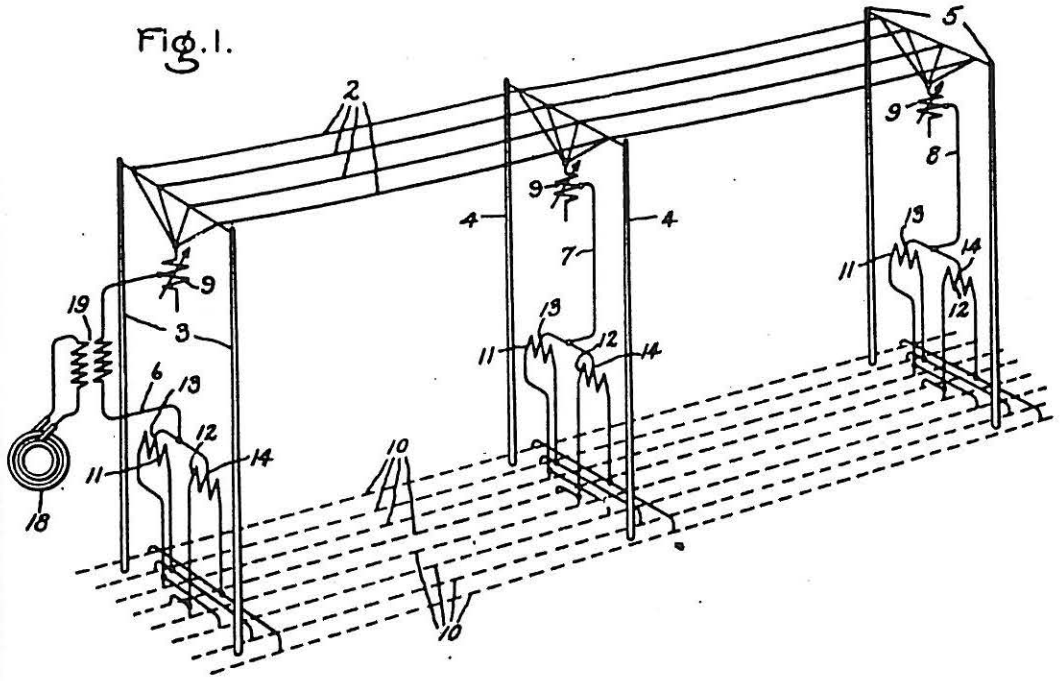
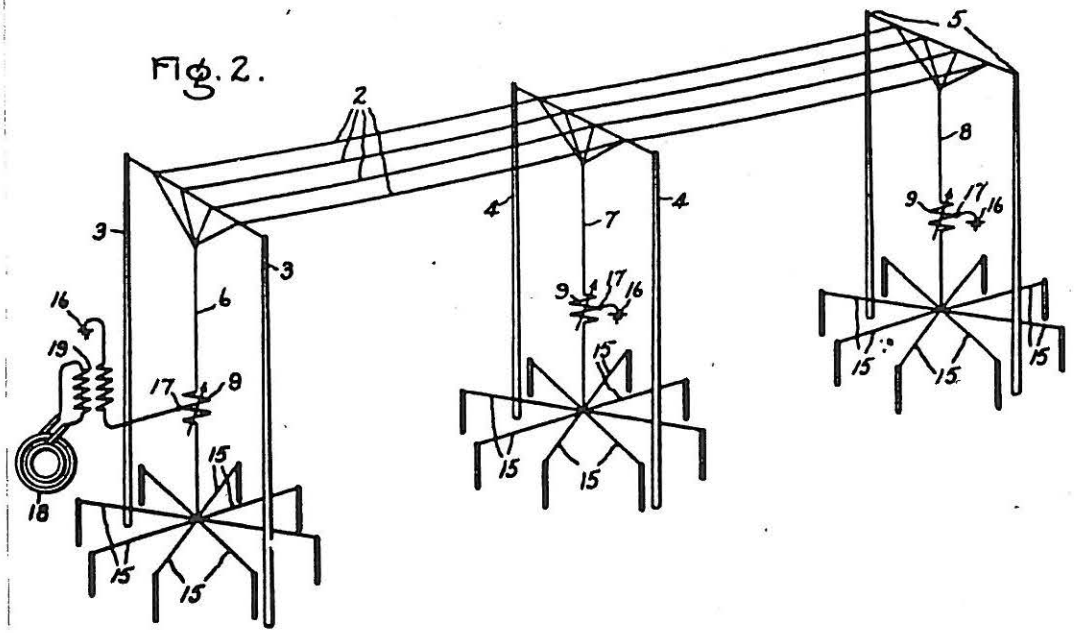


Fig. 2.



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UNITED STATES PATENT OFFICE.

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ANTENNA.

1,360,168. Specification of Letters Patent. Patented Nov. 23, 1920.

Application filed February 15, 1918. Serial No. 217,379.

To all whom it may concern:

Be it known that I, ERNST F. W. ALEXANDERSON, a citizen of the United States, residing at Schenectady, in the county of Schenectady, State of New York, have invented certain new and useful Improvements in Antennæ, of which the following is a specification.

My present invention relates to antennæ for radio signaling systems and more particularly to ground connections for a radiating antenna system.

One method which has heretofore been employed for grounding an antenna consists in burying a network of ground conductors beneath the antenna, covering an area of about the same order of magnitude as that covered by the elevated conductors and connecting the antenna to a single point in this network. With such an arrangement there is a tendency for the conductors or the portion of the network nearest the ground connection to collect nearly all of the ground current while those portions located farthest from the ground connection collect but very little current. As a result the ground resistance of the system is much greater than it would be if the ground current were equally divided among all of the conductors.

One of the objects of my invention is to secure a system of connections to the ground conductors which is arranged in such a way that the current in the ground will be divided substantially equally among all of the buried conductors, and the ground resistance will be a minimum.

In attaining this object I provide a plurality of connections between the antenna and the ground conductors at points distributed as uniformly as possible over the area covered by the overhead system. This may conveniently be done by arranging a system of conductors which are elevated a short distance above the earth and which extend in multiple, from the lower end of the usual vertical conductor coming down from the aerial, to each of the points chosen in the buried system. By a suitable arrangement of balancing coils the connections may be made to the vertical conductor in such a way as to cause equal current to flow in all of the ground connections.

A further object of my invention is to provide means for reducing the ground resistance of the system to a value lower than that which can be obtained with the grounding system described above and at the same time retain all of the advantages of a system having a direct ground connection.

In attaining this object of my invention I provide a capacity ground constructed in a similar manner to an insulated counterpoise and operate this capacity ground in multiple with the buried network. This capacity ground is connected to the aerial through a greater impedance than the impedance connecting the aerial to the buried network so that in effect the potential impressed thereon is ultranegative with respect to that impressed upon the buried network.

The novel features which I believe to be charactertistic of my invention are set forth with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation together with further objects and advantages thereof will best be understood by reference to the following description taken in connection with the accompanying drawing in which Figure 1 shows diagrammatically a method of connecting the antenna to the grounding system and Fig. 2 shows the application of capacity grounds to the antenna.

As indicated in Fig. 1 the radiating antenna comprises a plurality of horizontal wires 2 supported by the towers 3, 3; 4, 4; and 5, 5. Vertical conductors 6, 7 and 8 are provided for connecting the antenna to ground at each pair of supporting towers. This method of providing multiple grounds for an antenna is described and claimed in my co-pending application, Serial No. 191,110, filed Sept. 13, 1917, which is a continuation of my application, Serial No. 123,276 filed October 2, 1916. Each of these vertical conductors includes the usual loading coil 9. A ground for the system is obtained by means of a plurality of conductors 10 buried in the earth beneath the antenna and extending over an area as large as or somewhat greater than that covered by the antenna. In employing a ground of this type it has been customary to connect all of the buried conductors together by underground conductors and to connect a single point in the network to the lower end of the vertical con-

ductor. With such an arrangement however, the part of the network, nearest the point of connection will collect the greater part of the current and as a result the ground resistance is greater than it would be if all equal portions of the network collected equal currents. I have overcome this disadvantage by providing connections above the earth between the lower ends of vertical conductors 7 and each of the buried conductors 10. In order to make these connections in such a way that the current will divide equally among all of the conductors I have, in the system illustrated, provided balancing coils 11 and 12 and connected the vertical conductors 6, 7 and 8 to points 13 and 14 between the ends of these coils as indicated. One end of balancing coil 12 is connected to the two outer conductors of the buried system and the other end is connected to the two central conductors. One end of balancing coil 11 is connected to the two conductors immediately adjacent the outer conductors and the other end is connected to the two conductors immediately adjacent the central pair of conductors. By properly choosing the points of connection 13 and 14 the potentials in the grounding system may be so balanced that the ground current will be equally divided among all of the conductors and under these conditions the multiple resistance will be a minimum.

I have found that the ground resistance may be reduced still more by employing capacity grounds in multiple with the system of buried conductors as indicated in Fig. 2. In the present case the capacity grounds consist of a plurality of horiontal conductors 15 radiating from the foot of the vertical conductors 6, 7 and 8 and insulated from earth. The conductors 15 are all connected to the lower ends of the loading coils 9 and the ground conductors 16 which may be of the form shown in Fig. 1 or any other desired form are connected to the points 17 which are located between the two ends of the loading coils. By connecting the capacity ground to the loading coils in this way the potential impressed thereon will be ultra negative with respect to that on the ground conductors.

Capacity grounds, or radial counterpoises have been used heretofore without any direct connection to earth. The object of the counterpose in such a case is to prevent the electrostatic lines from passing through the ground, the counterpoise acting as a screen between ground and antenna in such a way that the electrostatic lines go directly to the counterpoise. Such a counterpoise has an indefinite or floating electrostatic potential and is not grounded at all. In the arrangement which I have described, however, the capacity ground does not function in the same manner as the usual counterpoise as its principal function is to draw current from the ground. Hence the contact between the antenna and ground includes not only the contact surface of the buried wires but also the capacity connection between the conductors 15 and ground.

I have found that by using the two methods of grounding in conjunction with each other the ground resistance of the antenna is reduced to a value lower than can be obtained with either one separately. The use of a grounded system instead of a floating counterpoise also has several practical advantages. The alternator 18 which supplies current to the antenna through the transformer 19 is connected to a ground circuit and is therefore protected from static potentials. The antenna itself is also protected from atmospheric disturbances by being permanently grounded at several points through the different loading coils.

While I have shown and described only one way in which each of the two features of my invention may be carried into effect it will be apparent that many modifications in the specific application of my invention may be made without departing from the s ope of the appended claims.

What I claim as new and desire to secure by Letters Patent of the United States, is:—

1. A grounding system for a radiating antenna comprising a plurality of paths to ground of unequal length from the lower end of a vertical conductor extending downwardly from the antenna, and inductive means for distributing the current through the several paths in such a way as to obtain a minimum multiple resistance.

2. A grounding system for a radiating antenna comprising a plurality of paths to ground of unequal length from the base of a vertical conductor extending downwardly from the antenna, and inductive means for distributing the current in substantially equal parts among the different paths.

3. A radiating antenna system comprising an elevated network extending over a considerable area and supplied with radio frequency current, a system of conductors buried in the ground beneath said network, a plurality of connecting wires carrying the charging current of the network to points in the system of ground conductors located at unequal distances from the lower end of a vertical conductor extending downwardly from the network, and inductive means for distributing the current in substantially equal parts between the different points in the ground system.

4. A radiating antenna system comprising a plurality of elevated conductors extending over a considerable area and supplied with radio frequency current, a system of conductors buried in the earth beneath said elevated conductors, a vertical

conductor extending downwardly from said elevated network and connecting conductors from the lower end of said vertical conductor to a plurality of points in said system of buried conductors which are located at unequal distances from the lower end of said vertical conductor, all of said connecting conductors being elevated above the earth and being connected to the system of buried conductors in such a way that the current in the system will be divided substantially equally among all of said connecting conductors.

5. A radiating antenna system comprising a plurality of horizontal elevated conductors extending over a considerable area and supplied with radio frequency current through a ground connection, a plurality of separate ground conductors buried in the earth extending from said ground connection parallel with the elevated conductors, and a plurality of connecting conductors between the lower end of a vertical conductor extending downwardly from the elevated conductors and said ground conductors, all of said connecting conductors being elevated above the earth and being connected to said ground conductors in such a way that the current in the system will be divided substantially equally among all of said connecting conductors.

6. A radiating antenna system comprising an elevated conducting network extending over a considerable area and supplied with radio frequency current, a plurality of vertical conductors extending downwardly from said network at points substantially uniformly distributed in said network, a system of ground conductors buried in the ground beneath said network, a plurality of connecting wires extending from the lower end of each vertical conductor to points in the system of ground conductors located at unequal distances therefrom, and means for distributing the antenna current in substantially equal parts between the different points in the ground system.

7. A radiating antenna system comprising a plurality of substantially horizontal elevated conductors extending over a considerable area and supplied with radio frequency current, a system of ground conductors buried in the earth and extending parallel with said elevated conductors, a plurality of vertical conductors extending downwardly from said elevated conductors, and a plurality of connecting conductors extending from the lower end of each vertical conductor to points in the system of ground conductors located at unequal distances therefrom, and inductive means for distributing the antenna current in substantially equal parts between the different points in the ground system.

8. A grounding system for a radiating antenna system comprising both a conductive and a capacity path to ground from a vertical conductor leading downwardly from the antenna, said ground path comprising connections to a plurality of ground points located at unequal distances from the base of the vertical conductors, and inductive means for distributing the current to the several ground points in such a way as to obtain a minimum multiple resistance.

9. A radiating antenna system comprising an elevated conducting network extending over a considerable area and supplied with radio frequency current, a plurality of ground connections for said elevated system, a second system of conductors insulated from earth extending over the area between said network and earth, and connections between the elevated network and said second system of conductors including means whereby a potential is impressed thereon which is ultranegative with respect to the earth potential of the system.

10. A grounding system for a radiating antenna comprising a ground conductor buried in the earth and extending over an area of the same order of magnitude as that covered by the antenna and a system of conductors insulated from the ground and connected to the antenna in such a way that the antenna current will divide between the ground conductor and the insulated system.

11. A radiating antenna system comprising an elevated conducting network extending over a considerable area and supplied with radio frequency current, a system of ground conductors buried in the earth beneath said network and extending over an area of the same order of magnitude as said network and a system of conductors elevated above the earth and insulated therefrom, and connected to said network in such a way that the antenna current will divide between the ground conductors and the insulated system.

12. A radiating antenna system comprising a plurality of substantially horizontal elevated conductors supplied with radio frequency current, a ground connection for said elevated conductors, a horizontal conducting network insulated from earth and connections from said elevated conductors to said conducting network whereby a potential is impressed on said conducting network which is ultra-negative with respect to the earth potential of the system.

13. A radiating antenna system comprising an elevated conducting network supplied with radio frequency current, an inductance having one terminal connected to said elevated network and its other terminal connected to a second system of conductors which is insulated from earth and extends over the area between the elevated network and earth, and a ground connection to an intermediate point in said inductance.

14. A radiating antenna system comprising an elevated conducting network extending over a considerable area, a plurality of vertical conductors extending downwardly from said network, a ground connection for each of said vertical conductors, a second system of conductors insulated from the earth and extending over the area between said network and earth, and connections between each of said vertical conductors and said second system of conductors whereby a potential is impressed thereon which is ultra-negative with respect to the earth potential of the system.

In witness whereof, I have hereunto set my hand this 14th day of February, 1918.

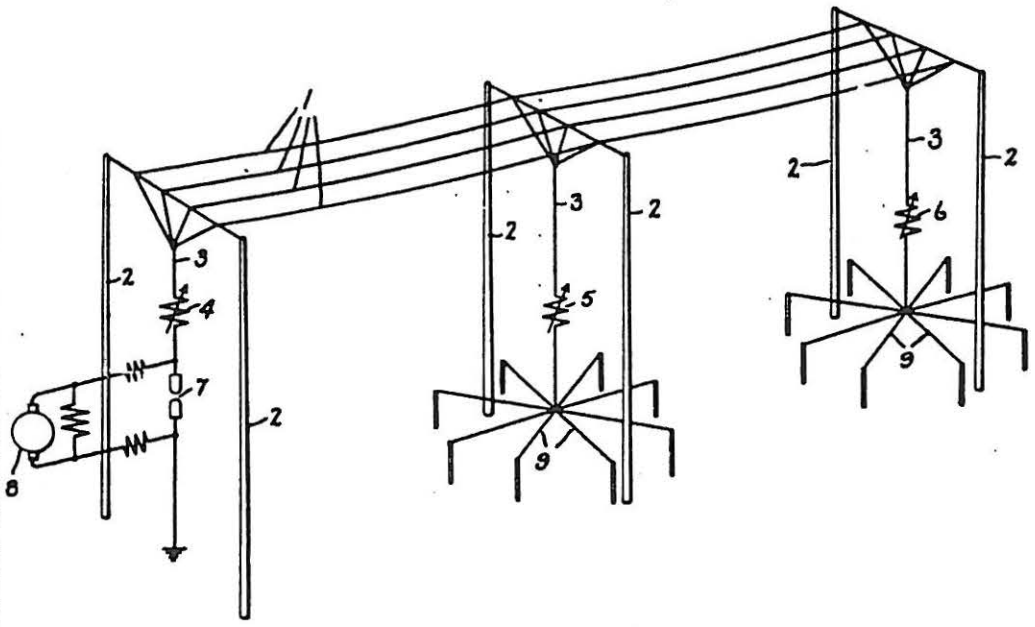
ERNST F. W. ALEXANDERSON.

E. F. W. ALEXANDERSON.

RADIOSIGNALING SYSTEM.

APPLICATION FILED DEC. 24, 1918.

1,360,169. Patented Nov. 23, 1920.



Inventor:
Ernst F.W. Alexanderson,
by Albert G. Davis
His Attorney.

UNITED STATES PATENT OFFICE.

ERNST F. W. ALEXANDERSON, OF SCHENECTADY, NEW YORK, ASSIGNOR TO GENERAL ELECTRIC COMPANY, A CORPORATION OF NEW YORK.

RADIOSIGNALING SYSTEM.

1,360,169. Specification of Letters Patent. Patented Nov. 23, 1920.

Application filed December 24, 1918. Serial No. 268,128.

To all whom it may concern:

Be it known that I, ERNST F. W. ALEXANDERSON, a citizen of the United States, residing at Schenectady, in the county of Schenectady, State of New York, have invented certain new and useful Improvements in Radiosignaling Systems, of which the following is a specification.

My present invention relates to radiosignaling systems and particularly to a method of adjusting a radiating system supplied with energy from an arc generator, to obtain a high degree of efficiency.

In my prior applications, Serial No. 123,276, filed October 2, 1916, and Serial No. 191,110, filed September 13, 1917, I have described and claimed a radiating antenna system which is of high efficiency by reason of the fact that a plurality of ground connections for the aerial are provided with a tuning coil in each ground connection. The antenna described in the aforesaid applications is supplied with energy from a high frequency alternator and, when the various tuning coils are properly adjusted to obtain the most efficient combination of alternator and antenna, acts in effect as a plurality of substantially independent radiators. In this case, the entire energy from the alternator is supplied to one of these radiators and this radiator in turn supplies energy to the other radiators.

By reason of this method of operation the feed resistance of the antenna or the apparent resistance of the circuit which is fed by the alternator as determined from the energy output and the current supplied to the first radiator, is much greater than when the antenna system is operated as a single radiator. For example, in the case of one long horizontal antenna to which my prior invention has been applied, the feed resistance when operating as a single radiator was 3.6 ohms and when six ground connections with tuning coils were provided so that the antenna operated as six substantially independent radiators, the feed resistance increased to about 20 ohms. This increase of feed resistance does not affect the efficient operation of the system when a high frequency alternator is used as a source of energy. In case, however, it is desired to use an arc generator as a source of supply a different situation is presented. The characteristics of the arc are such that it will operate most efficiently and deliver its maximum output with a given value of resistance in the circuit to which it supplies energy. This resistance may be from two to four ohms. In the case above mentioned then the arc generator might deliver its maximum output when a single ground connection was employed and the antenna acted as a single radiator. As I have pointed out, however, in my co-pending applications mentioned above, the antenna when supplied with a given amount of energy will operate most efficiently when it is adjusted to act as a plurality of substantially independent radiators. Hence it appears that if the arc is to deliver its maximum output the advantages of multiple tuning must be sacrificed while if all of the advantage of multiple tuning is to be obtained the arc output and efficiency will be greatly reduced. In practice a compromise between these two extremes will be found to produce the maximum strength of signals from a given combination and the object of my invention is to provide a method of adjusting the radiating system so as to give the greatest possible radiation.

In carrying my invention into effect I provide a plurality of ground connections with tuning coils therein and place the arc generator in one of these ground connections. The various tuning coils are then adjusted until a point is reached where the total of the charging currents in the different ground connections is a maximum. The charging current in the ground connection supplied by the arc will then be greater than that in the other ground connections but may be less than it would be if the other connections were omitted. The total of all of the charging currents, however, will be greater than the current which would be supplied by the arc if only one ground connection were employed, although the total output of the arc will be less. The feed resistance of the circuit supplied by the arc will be greater than it would be if a single ground connection were used but will be less than it would be if the antenna were adjusted to obtain the full advantage of multiple tuning with a high frequency alternator. In effect the antenna will act in part as a single radiator and in part as a plurality of substantially independent radiators. Part of the energy will be supplied to

the antenna in the same manner as when a single ground connection is used and part will be supplied at high voltage from the first independent radiator to the other sections of the antenna which act as independent radiators in the same manner as when the full advantage of multiple tuning is obtained.

The novel features which I believe to be characteristic of my invention are set forth with particularity in the appended claims, the invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, will best be understood by reference to the following description taken in connection with the accompanying drawing in which I have illustrated diagrammatically one way in which my invention may be carried into effect.

In the drawing I have indicated an antenna of the horizontal type and comprising a plurality of wires 1, supported by the usual towers 2. At each of these supporting towers I provide grounding connections 3 containing tuning coils 4, 5 and 6. The arc generator which is indicated at 7 and which is supplied with current from the usual direct current source 8 is placed in the first of these ground connections. This arc generator may consist of any well known form of arc device which is adapted to produce high frequency oscillations. The grounds which are provided at the other points are in the form of capacity grounds 9 consisting of a network of wires supported a short distance above the ground. The capacity ground is used in this case to prevent the short circuiting of the direct current generator 8 which supplies energy to the arc 7.

In the operation of this system to obtain the maximum radiation the adjustment of tuning coils 4, 5 and 6 is varied, and the charging currents in the different connections observed until an adjustment is arrived at where the total of the different charging currents becomes a maximum. When this condition is reached the system will operate at its greatest efficiency as a radiator since the amount of energy radiated is proportional to the sum of the separate charging currents.

In the system which is illustrated and described in the co-pending applications above mentioned, the various tuning coils are ordinarily so adjusted that the charging currents in all of the ground connections are substantially equal. Under these conditions the effective inductance in the tuning coils will be of such value as to neutralize the capacity of that portion of the aerial which is adjacent the ground connections in which the individual tuning coils are inserted. With this adjustment the antenna as here shown would operate as three substantially independent radiators. When the arc generator is employed as a source of energy, however, the operation of the system in this manner will not give the maximum radiation because of the fact that the feed resistance of the circuit to which the arc is supplying its energy may be much greater than the resistance at which the arc operates to give its maximum output. As a result it will be found that when the system is adjusted, as described above, to secure maximum value of the total charging current, that the charging current through the tuning coil 4 will be greater than that through coils 5 and 6. This indicates that the inductance of the coils 5 and 6 is not great enough to neutralize entirely the capacity of those sections of the aerial which are adjacent to the ground connections of these coils and which would naturally be fed through these ground connections. This means that the inductance of the coil 4 must be of such value that it will neutralize the capacity of the section of the aerial adjacent to its ground connection and will also neutralize a portion of the capacity of those sections which are supplied through the coils 5 and 6. While the actual operation of the antenna under these conditions may be somewhat complex, it may be assumed for all practical purposes that the antenna is operating in part as a single radiator and in part as a plurality of substantially independent radiators. A portion of the energy supplied by the arc will be furnished to the antenna in the same manner as though the antenna were acting as a single radiator. That section of the antenna which is adjacent the first ground connection will also act as an oscillation transformer and a portion of the energy will be supplied to the other sections of the antenna from this first portion at a high voltage.

In the adjustment of the system such as that which I have described in which a plurality of ground connections with tuning coils therein are employed, it may be found desirable, in order to obtain the most favorable value of the feed resistance, to disconnect entirely one or more of the ground connections nearest the connection through which energy is applied to the antenna. In the claims which follow, therefore, where I refer to an adjustment of the tuning coils, I mean to include the actual disconnection of one or more of these coils.

While I have illustrated a single embodiment of my invention, it will be apparent that it is not limited to the particular form of antenna indicated or to the particular arrangement of ground connections indicated, but that it may be applied to any desired form of antenna in which a plurality of ground connections with tuning coils therein are provided.

What I claim as new and desire to secure by Letters Patent of the United States, is:

1. The method of obtaining a desired value of feed resistance in an antenna having a plurality of grounding connections with tuning coils therein, and having means for introducing the energy through one of the ground connections which consists in neutralizing a portion only of the distributed capacity of the antenna adjacent each ground connection by means of the tuning coils therein and neutralizing the remainder of the distributed capacity of the antenna by means of the tuning coil in the connection through which the energy is introduced to the antenna.

2. The method of operating a radiating system comprising an antenna having a plurality of grounding connections with tuning coils therein which consists in adjusting the tuning coils in such a way that the charging currents in the different ground connections are unequal and the antenna acts in part as a single radiator and in part as a plurality of substantially independent radiators.

3. The method of operating a radiating system comprising an antenna having a plurality of grounding connections with tuning coils therein and supplied with energy by an arc generator which consists in varying the adjustment of the different tuning coils until a point is reached at which one of the ground connections carries a greater charging current than the others and the sum of the charging currents in the individual ground connections becomes a maximum.

4. The method of operating a radiating system comprising an antenna having a plurality of grounding connections with tuning coils therein and supplied with energy by an arc generator which consists in adjusting the feed resistance of the circuit to which energy is supplied by the generator to a value at which the sum of the charging currents in the individual ground connections becomes a maximum by varying the values of the charging currents in the different ground connections so that the charging currents in different ground connections have different values.

5. The combination in a radiating system of an antenna having a plurality of grounding connections with tuning coils therein and an arc generator for supplying high frequency energy to said radiating system, said tuning coils being so adjusted that the charging currents in different ground connections will have different values and the feed resistance of the circuit to which energy is supplied having such a value that the sum of the charging currents produced in the individual ground connections is a maximum.

6. The combination in a radiating system of an antenna having a plurality of grounding connections with tuning coils therein and an arc generator connected to one of said ground connections for supplying energy to said antenna, said tuning coils being so adjusted that the charging current in the ground connection through which energy is supplied is of different value than that in the other ground connections and the sum of the charging currents in the individual ground connections is a maximum.

7. The combination in a radiating system of an antenna having a plurality of grounding connections with tuning coils therein and an arc generator for supplying high frequency energy to said radiating system through one of said grounding connections, said tuning coils being so adjusted that the charging current through the ground connection through which energy is supplied will be greater than the charging currents in the other ground connections and the antenna will act in part as a single radiator and in part as a plurality of substantially independent radiators.

8. The combination in a radiating system of an antenna having a plurality of grounding connections with tuning coils therein and having means for introducing the energy through one of the ground connections, each of said tuning coils in the other ground connections being so proportioned as to neutralize a portion only of the distributed capacity of the antenna adjacent its ground connection and the tuning coil in the ground connection through which energy is supplied having such a value as to neutralize the remainder of the distributed capacity of the antenna.

In witness whereof I have hereunto set my hand this 23rd day of December, 1918.

ERNST F. W. ALEXANDERSON.

Nov. 24, 1925. 1,562,961

R. A. HEISING

DIRECTIVE RADIO TRANSMISSION SYSTEM

Filed May 16, 1921 4 Sheets-Sheet 1

Fig. 1

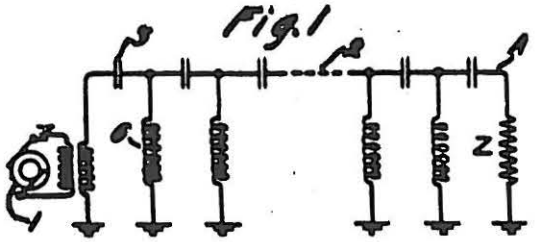


Fig. 2

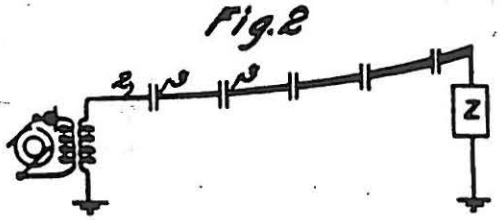


Fig. 4

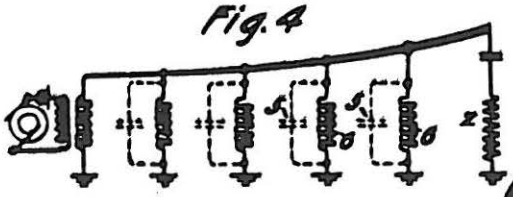


Fig. 5

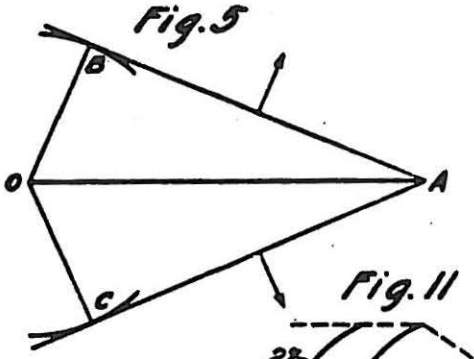


Fig. 3

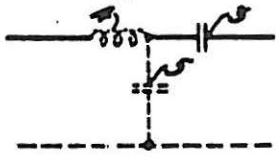


Fig. 11



Fig. 6

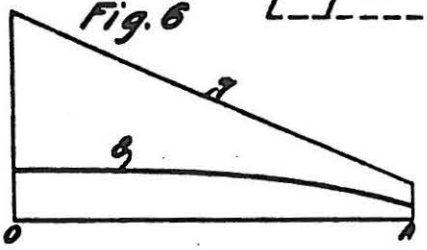


Fig. 10

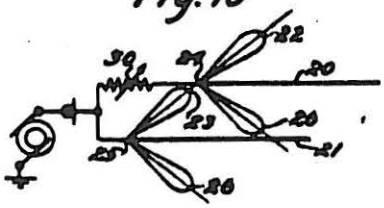


Fig. 7

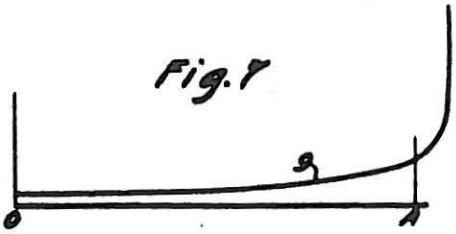
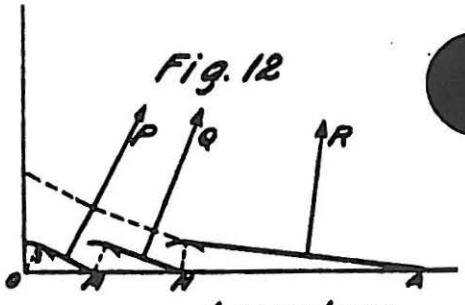


Fig. 12



Inventor:
Raymond A. Heising
by C. C. Sprague Att'y.

Nov. 24, 1925. 1,562,961

R. A. HEISING

DIRECTIVE RADIO TRANSMISSION SYSTEM

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Fig. 8

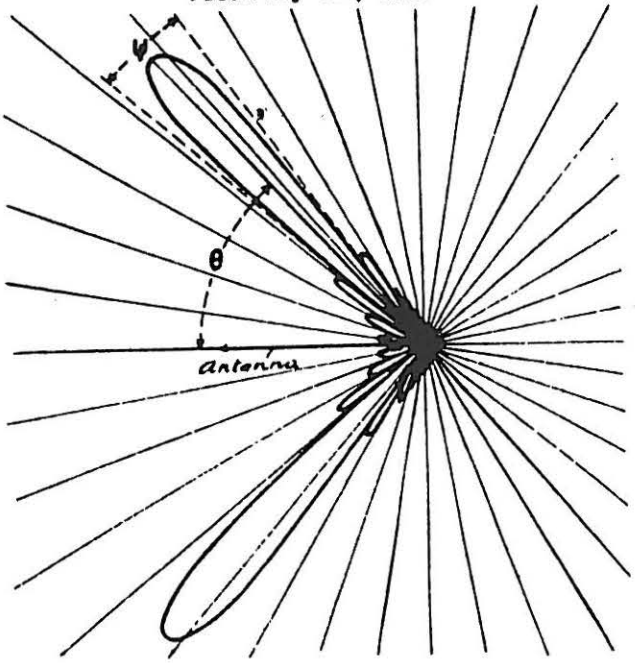
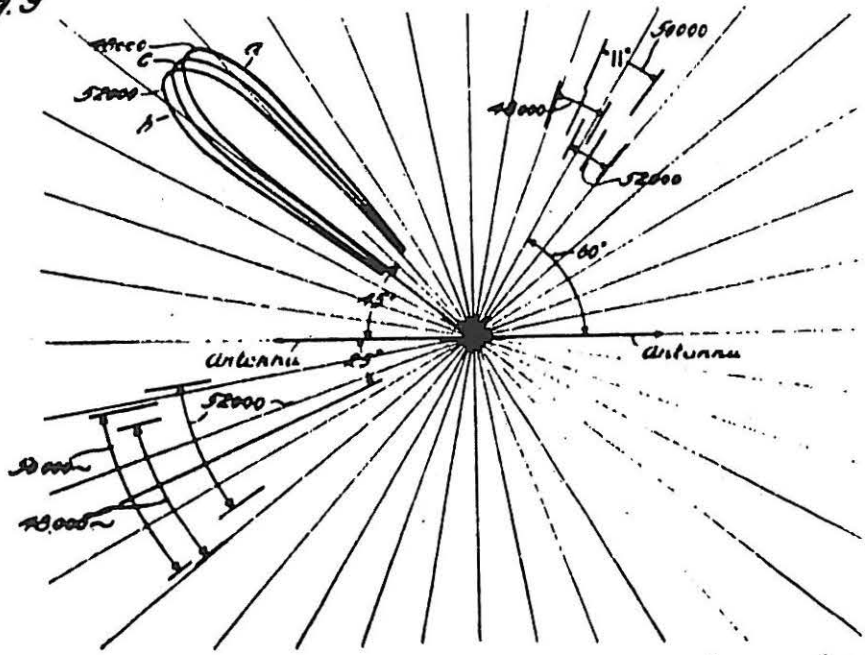


Fig. 9



Inventor:
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by C. C. Sprague. Att'y.

Nov. 24, 1925. 1,562,961

R. A. HEISING

DIRECTIVE RADIO TRANSMISSION SYSTEM

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Fig. 13

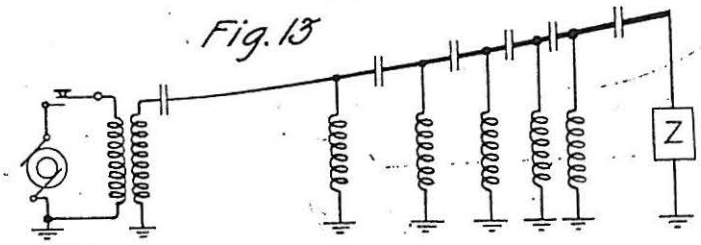


Fig. 14

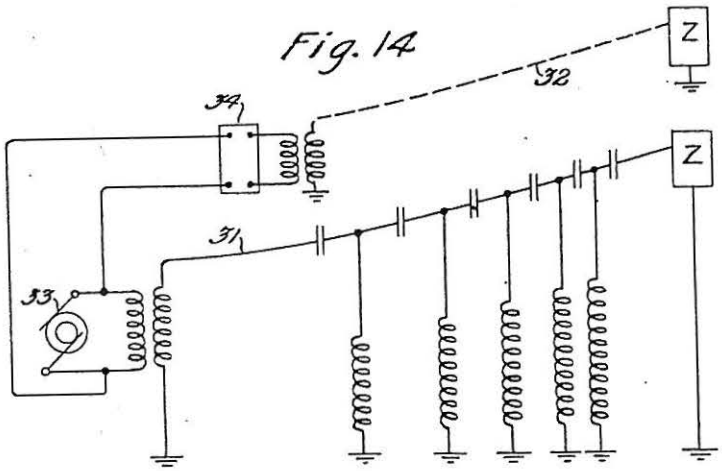


Fig. 16

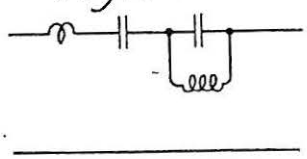


Fig. 15

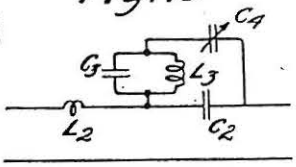
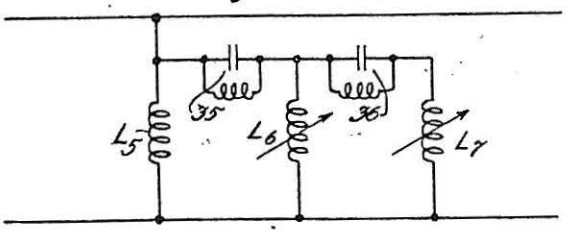


Fig. 17



Inventor:
Raymond A. Heising
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Nov. 24, 1925. 1,562,961

R. A. HEISING

DIRECTIVE RADIO TRANSMISSION SYSTEM

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Fig. 18

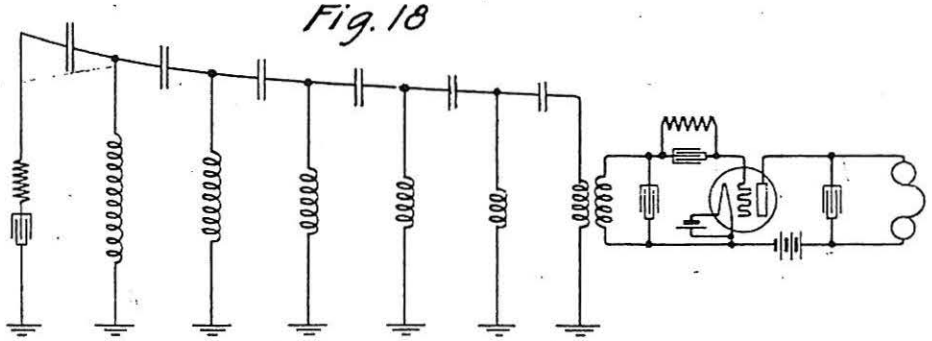
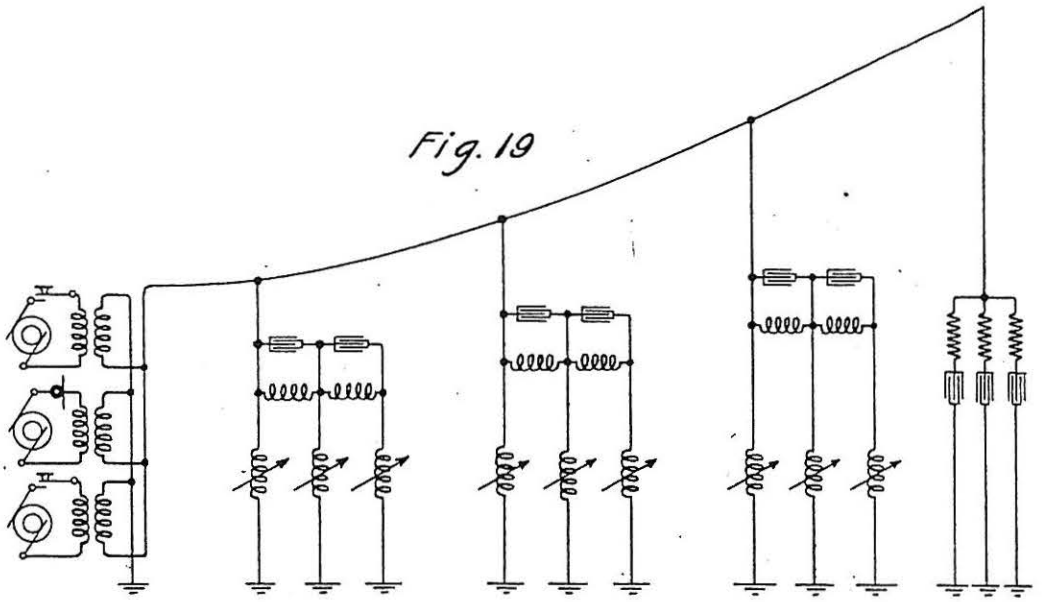


Fig. 19



Inventor:
Raymond A. Heising
by C. C. Sprague. Att'y

Patented Nov. 24, 1925. 1,562,961

UNITED STATES PATENT OFFICE.

RAYMOND A. HEISING, OF MILBURN, NEW JERSEY, ASSIGNOR TO WESTERN ELECTRIC COMPANY, INCORPORATED, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK.

DIRECTIVE RADIO TRANSMISSION SYSTEM.

Application filed May 16, 1921. Serial No. 470,042.

To all whom it may concern:

Be it known that I, RAYMOND A. HEISING, a citizen of United States of America, residing at Milburn, in the county of Essex, State of New Jersey, have invented certain new and useful Improvements in Directive Radio Transmission Systems, of which the following is a full, clear, concise, and exact description.

This invention relates to directive transmission of energy and more particularly to methods of and systems for directively radiating and absorbing electric waves.

An object of the present invention is to provide a transmission system for radiating energy directively. Another object of the invention is to provide a focussing antenna which will concentrate the radiated energy at a distant point.

The propagation velocity of wave in any medium is in general the product of its frequency and its wave length in that medium. In the case of free electric waves, the propagation velocity is approximately 300,000,000 meters per second. In the case of guided electric waves, the wave length and the wave propagation velocity are functions of the electrical constants of the guiding transmission conductors. As given by Heaviside, the wave lengths of a sustained wave over a circuit having uniformly distributed inductance and capacity is

$$(1)\quad \lambda = \frac{2\pi}{\sqrt{\frac{1}{2}\left\{\sqrt{(SR+\omega^2LC)^2+\omega^2(LS-CR)^2}-(SR-\omega^2LC)\right\}}}$$

where λ is the wave length, ω is the angular velocity or the wave frequency multiplied by 2π and S, R, L, and C are respectively the shunt conductance, series resistance, series inductance, and shunt capacity of the circuit per unit length. This wave length evidently depends upon the magnitudes of these four electrical characteristics per unit length of the circuit. By varying these it is possible to increase or decrease the wave length of the sustained wave and accordingly to vary the wave propagation velocity along the circuit. If a loaded circuit of this character is used for radiating or absorbing electric waves, the waves, if sustained sine waves, may be propagated along the circuit at a greater velocity than that at which they progress in the ether. If a definite small part of a transmitting antenna be considered, the energy of the wave proceeding from that part will be partly propagated along the circuit as a guided wave and partly radiated and propagated out through the surrounding space. The shape of the resultant wave front in the ether will be dependent upon the relative velocities of wave propagation in the two media. It is, therefore, possible to give a radiated wave variously directed fronts depending upon the loading of the antenna circuit. It is likewise possible to so absorb the directed radiant wave at a receiving antenna as to cause all of the absorbed energy to cumulatively affect the receiving device.

According to the present invention a radio transmitting or receiving antenna is made long with respect to the wave-length of the wave to be transmitted or received. In order to make this antenna behave as a conductor of infinite length and thereby avoid the production of a reflected wave, it is desirable to terminate it in an impedance element having an impedance equivalent in magnitude and character to the iterative or surge impedance of the antenna itself at the terminating point. At intervals corresponding to a fraction of a wave-length, the antenna is loaded by inserting series capacity or shunt inductance or both to make its wave propagation velocity for the waves to be transferred higher than the corresponding wave propagation velocity in ether. Since the energy in a radiating antenna decreases with increasing distance from the source, it is desirable in order to secure the best results to progressively increase the radiating factor of the antenna and this is done by increasing its height.

The invention permits radiation in one lateral direction to the substantial exclusion of radiation in any other by an arrangement of parallel antennæ. For focussing on a

fixed receiving point the loading of the transmitting antenna may be progressively increased so as to progressively change the direction of the wave front of the emitted wave. The antenna may also be curved laterally to add to the focussing effect. For multiplex operation, waves of a plurality of different frequencies may be focussed at the same or different points by loading the antenna in different manners for waves of each of the different frequencies.

Other objects of the invention will be apparent upon consideration of the following detailed description taken in connection with the accompanying drawing in which Figure 1 illustrates diagrammatically a loaded antenna long with respect to the wave length of the emitted wave; Figure 2, a radio transmission arrangement including series capacity loading for increasing the wave propagation velocity; Figure 3, a unit section of the conductor of Figure 2; Figure 4, an antenna system provided with shunt inductance loading; Figure 5, a diagram indicating the directive operation of loaded antennæ; Figure 6, a diagram of current and energy distribution in antennæ of the type disclosed; Figure 7, the radiating coefficient diagram for antennæ of this type; Figure 8, a polar diagram showing the distribution of the radiated wave amplitude in various angular zones; Figure 9, a polar diagram showing the distribution of energy of a modulated carrier wave; Figure 10, an antenna system for neutralizing the directed energy in one direction; Figure 11, an arrangement of laterally curved antennæ for focussing energy at a distant receiving station; Figure 12, a diagram indicating the operation of a second type of focussing system depending upon progressive change in loading; Figure 13, an antenna arrangement for this second type of system; Figure 14, a directive focussing system employing both capacity and inductance loading; Figures 15 to 17 illustrate details of loading arrangements applicable to any of the foregoing systems; Figure 18, a receiving system with a loaded antenna; and Figure 19, a multiplex system for focussing a plurality of different waves.

Referring to Figure 1, a source 1 is associated with an antenna 2 to supply energy thereto for radiation. Antenna 2 is preferably of a length several times the wave-length defined in equation (1). This wave-length depends upon the inductance and capacity per unit length of the radiating circuit. In loaded telephone lines with inductances, as is the common practice, the wave-length is greatly shortened. In fact, in loaded line telephone practice, the wave-length multiplied by the frequency may give a velocity of the order 90,000,000 meters per second instead of 300,000,000 meters per second which is the velocity of light and of free electric waves. Since increasing the inductance per unit length which is done in loading telephone lines, shortens the wave-length at a given frequency, it will be evident that it is possible by reducing the inductance per unit length, to increase the wave-length of a unit circuit. If the resistance and shunt conductance of the circuit are made zero, equation (1) reduces to

$$(2)\quad \lambda = \frac{2\pi}{\omega\sqrt{LC}}$$

From equation (2) it would appear that, with circuits of negligible series resistance and shunt conductance per unit length, either reducing the series inductance per unit length or the shunt capacity per unit length, should increase the wave length and, therefore, increase the velocity at which a given frequency wave is propagated along the circuit. This can actually be accomplished in several ways it being remembered that the long antenna with its capacity to ground and the return ground conducting path may, if uniform and if properly terminated, be treated as any other alternating current conducting circuit. One simple way to increase the velocity of the wave propagation is illustrated in Fig. 1 in which series loading capacities 3 and shunt inductances 6 are inserted in the conducting line and are spaced much in the same manner as are the loading inductances in loaded telephone lines. These loading inductances and capacities should be separated by distances small compared to a wave length, so that the effect of uniform distribution of the capacity is approximated. Although the exact number of such elements may vary greatly, it is desirable to use eight or more per unit length. For simplicity only a few elements are shown. The action of this capacity loading is to introduce series reactance opposite in sign to that of the natural series inductance, and accordingly to produce lower effective series inductance per unit length. The action of the inductance loading is to introduce shunt reactance opposite in sign to that of the natural shunt capacity and hence to produce lower effective shunt capacity reactance per unit length. It will, of course, be understood that either series capacity loading or shunt inductance loading alone may be used.

As has been previously mentioned, a circuit of this character of finite length must be properly terminated to avoid having a wave reflected from the free terminal. A reflected wave produces nodes along the circuit and introduces complications of various sorts. If the transmitted wave gives directive radiation in the general direction of its transmission the reflected wave will give

directive radiation in the opposite direction. To eliminate the reflected wave and prevent this reverse transmission, it is only necessary to terminate the line with a proper impedance Z, the value of which may be computed from well known transmission equations.

Fig. 2 illustrates a modification of the arrangement of Fig. 1 in which series capacity loading is employed. Conductor 2 is progressively elevated to increase the radiating factor so as to maintain the energy radiation as nearly equal as possible at all points along the antenna. To maintain the unit shunt capacity constant with increasing height a conductor of increasing size is employed. An element of the recurrent network thus formed is illustrated in Figure 3, in which the natural series inductance 4 and shunt capacity 5 of the conductor, both indicated by dotted lines, constitute together with the loading capacity 3 a uniform section of the line.

Fig. 4 illustrates another method of antenna loading which consists in reducing the effective shunt capacity of the circuit. This is accomplished by connecting between the line and ground, loading inductances 6 which are preferably spaced eight or more to the wave length, although in this case as well as in the case of the series capacity loading, a considerable variations in this number may be permitted. It is a well known fact that the effective capacity of a condenser is reduced by connecting in parallel with it a large inductance. The effective reactance of the condenser is increased. At a given frequency the natural capacity 5 of a unit section of the conductor with the inductance 6 shunted around it has several times the capacitative reactance which the capacity 5 alone has. Resistance tends to shorten the wave length. It is accordingly desirable to make the resistance of the antenna conductor very low. In loading systems of the kind described, the variations in effective capacity or effective inductance will be particularly marked for a given frequency, and wave velocities for such frequencies may be attained exceeding that of light.

The fact that a wave may be made to travel over a circuit with a velocity greater than that of free electric waves or light, may be made use of in directive transmission. Referring to Figure 5 in which OA represents a plan or top view of a long loaded antenna of the type illustrated in Figures 2 and 3, suppose that the source of waves is located at terminal O. An electrical disturbance occurring as an alternation of electrical potential at this point travels along the circuit to a point A. By radiation point O becomes the center of a disturbance of like form which emanates in all directions through space. If the space velocity i. e., the velocity of free electric waves is such that the radiated wave travels a distance OB during the time that the guided wave travels the distance OA, the wave front of the radiated wave in the space surrounding the antenna will take the directions BA and CA. The direction of propagation of the radiated wave being perpendicular to this front is indicated by the arrows. The angle between this wave front and the antenna evidently depends upon the ratio of the guided wave velocity to the free wave velocity. If right angle triangles are drawn similarly to Fig. 5 for the case where the base OA equals the radii OB and OC, the hypothenuses AB and AC will be infinitely short and at right angles to the base OA. This illustrates the critical case in which the ratio of velocities is unity. When this ratio is unity, the wave will accordingly be propagated in the direction of transmission along the circuit, i. e., OA. The physical basis for the phenomenon when the ratio is unity is made readily apparent by noting that as the wave is radiated in the direction of antenna OA, since the wave is propagated along the antenna at the same velocity, new centers of oscillation are continuously being established on the wave front which in turn gives rise to waves which travel in the direction OA coincidentally with those from the original wave source O and having the same phase. There accordingly results a reenforcing of the wave in the direction OA. The original wave and the waves radiated from these centers of oscillation in the opposite direction are opposed in phase and mutually extinguish each other. When the ratio is infinite the wave front will obviously be parallel to the conductor and the direction of propagation will be perpendicular to the antenna. When this ratio is less than unity, the antenna is not directive.

In Figure 4, the terminating element Z is shown as comprising series resistance and capacity. That the terminating impedance may be closely approximated by resistance alone will be evident from a consideration of the specification of United States patent to Heising 1,313,483, patented August 19, 1919.

In order to secure best results, the directed wave should be of uniform intensity throughout its wave front. This requires that the radiation in power should be the same for each unit length along the line. In a line having uniform resistance, inductance, and capacity, the current decreases logarithmically, and the radiation will accordingly be non-uniform. If the energy is to be uniformly radiated, the remaining energy in the guided carrier wave should decrease uniformly from the terminal O of the antenna to the terminal A, where the remainder of the energy should be absorbed by the terminating impedance Z. In order

to secure an energy distribution of this character as illustrated by line 7 of Figure 6, the current along the circuit must vary as the square root of the energy as represented by curve 8 of Figure 6. In order that the radiated power may be uniform along the line with decreasing current, it will be evident that the radiating constant of the antenna or its radiation resistance must be gradually increased along the line. It should vary according to the reciprocal of the square of the current amplitude, as indicated by curve 9 of Figure 7 which represents the radiation coefficient or radiation resistance. Since the radiation resistance varies approximately as the square of the height of the line, this variation in resistance may be secured by varying the height of the line so as to make this height approximately proportional to the square root of the required radiation resistance. This is indicated in Figures 2 and 4 in which the height of the line increases from the source to the remote terminal in accordance with the requirement just stated. The gradually increasing height with decreasing current will produce uniform radiation throughout the length of the conductor. Inasmuch as the energy remaining at A is absorbed in the terminating network Z, it is possible to terminate the line at such a point that the height of the antenna will not, because of the very small current, be required to exceed practical limits in order to maintain constant radiation.

With an antenna of varying height and a constant size conductor, the inductance and capacity per unit length will change. It is possible to progressively vary the magnitudes of the loading reactances along the line so as to maintain the wave velocity constant. As an alternative method the diameter of the conductor itself may vary progressively with the height. With this latter arrangement the loading inductances and capacities may remain the same per unit wave length if a constant wave velocity is to be maintained throughout the length of the conductor. Figures 2 and 4 indicate a variation in the diameter of the conductor to maintain the capacity per unit length substantially constant.

Figure 8 shows a complete radiation curve with the wave amplitude as a function of its angular direction from a particular loaded line antenna of twelve times the wave length. The position and direction of extension of the antenna is indicated by the arrow. The principal energy falls within a sector of a 14° angle marked *b*. Small amounts fall in other directions due to interference. Increasing the length of the antenna to twenty-four wave lengths would cut the angular width of the transmission loop in two and would reduce the size of the small loops representing power transmitted in other directions.

In radio telephony when modulating a carrier wave in accordance with speech, a band of waves of different frequencies results. If for example, a carrier wave of 50,000 cycles frequency is used and the range of the frequency of essential speech currents is about 2,000 cycles, the modulated energy will have frequencies ranging from 48,000 to 52,000 cycles. In a system of this kind these various frequency waves will travel along the loaded antenna with different velocities due to the fact that the effective inductive reactance or effective capacitive reactance per unit length changes with frequency. If a carrier wave of 50,000 cycles frequency is radiated from an antenna twelve wave lengths long, at a 45° angle, as shown by the curve of Figure 9, the 48,000 and 52,000 cycle frequency waves will be spread out in different directions, as shown by curves *a* and *b* respectively of the same figure. In this case the dispersion is not particularly harmful as there is sufficient amplitude of both of the extreme frequency waves occurring in the 45° angle direction to give a very good signal. Similary, if waves of this frequency are radiated in a 25° direction, as shown in the same figure, there will be a good quality of speech transmitted from the energy produced over an angle several degrees in width. If, however, the transmission angle is 60°, as shown in the same figure, the 52,000 and 48,000 cycle waves overlap very slightly and a change in quality is apt to result. In Fig. 9, the position and direction of extension of the antenna is indicated, for the respective directions of maximum directivity, in a manner similar to that of Fig. 8.

The transmission angle depends upon the propagation velocity. A larger transmission angle accordingly requires a large propagation velocity which in turn caus a larger difference between the propagati velocities along the line, of the different frequency components. Accordingly the differences in direction of the various frequency components, are accentuated as the transmission angle of the band as a whole is increased. If waves of frequencies lower than 50,000 cycles are used as a carrier, these variations will become still larger and it is, therefore, of advantage to use high carrier frequencies.

As is diagrammatically indicated in Fig 5, there is directive radiation in two lateral directions. An arrangement of multiple antennæ for suppressing radiation in one of these directions is illustrated in Figure 10 in which parallel directive antennæ 20 and 21 are so spaced that their respective energy transmission loops 22 and 23 from the terminals 24 and 25 connected with the

source extend in the same direction, and neutralize in space. If energy of the same phase is simultaneously supplied at points 24 and 25, and if these points are a half wave length apart in one direction in which their respective antennæ radiate most powerfully, the effect of the energy radiated from point 25 will be to oppose and neutralize that radiated from point 24 in this direction. This is for the reason that for all points in space in this direction these radiated energies will be opposite in phase. In other words loop 22 will neutralize loop 23. If the distance between the points 24 and 25 does not correspond to a half wave length, the phase of the energy supplied to one of the antennæ may be so shifted by a variable impedance device 30 that the points 24 and 25 will tend to radiate energies which will neutralize in space in the direction of the loops 22 and 23. This will leave only the loops 26 which are similarly directed and which are additive.

If it is desired to focus on a distant station, the directive antenna may be curved in direction as indicated in Figure 11 in which the two curved antennæ 27 and 28 are each given such curvature as to focus the radiated energy on a receiving station at 29. In general, in the case of curved antennæ it will be possible to obtain only roughly approximate neutralization by the use of two antennæ. Certain special cases, as for example, that where the antennæ extend along arcs of concentric circles and are arranged to focus their radiated energy at the center may give fairly exact neutralization.

A focussing effect could also be obtained by increasing the wave propagation velocity along the line so that in the region of one terminal of the line, the wave will be propagated at a greater rate than in the region of the other terminal. The operation of this will be clear from an inspection of Figure 12, in which an antenna OA is so loaded that a wave of given frequency applied at O will be propagated, in the first unit of time from O to M, in the second unit from M to N, in the third unit from N to A. Suppose that each portion OM, MN, and NA is, throughout its length, composed of like recurring sections. If the propagation velocity of the unguided waves when radiated be OS per unit of time, the radiated wave from portion OM will have a front, the direction of propagation of which is indicated by arrow P. The direction of the radiated wave of portion MN will be as indicated by Q, and that from portion NA as indicated by R. If the loading is made to progressively vary so that the wave length progressively varies, a smoothly curved wave front will obviously result. Figure 13 indicates diagrammatically an antenna loaded in this manner by a progressively closer spacing of the loading capacity or shunt inductance elements, or both. Instead of closer spacing of capacity elements of the same size the capacitances of the successively capacity elements may be progressively smaller, thus giving the same series capacity effect. In a similar manner instead of closer spacing of the shunt inductance elements, the shunt inductance elements may be uniformly spaced and their reactances may be progressively dimished in magnitude.

A desirable form of loaded antennæ is shown in Figure 14 in which the two antennæ 31 and 32, which may be either straight or laterally curved according to the arrangement of Figures 10 or 11, are arranged with corresponding points equidistantly spaced. A source 33 supplies energy to both these antennæ over parallel circuits one of which includes a phase changing device 34. This serves, as in the arrangement of Figure 10, to maintain the energies emitted from corresponding points of the two antennæ at the proper relative phases such that the energy radiated from one antenna will neutralize that radiated from the other in one direction. Each antenna comprises both series capacity and shunt inductance loading, thus combining the arrangement of Figures 2 and 4. The antennæ are progressively varied in height from the source to their remote terminals in order to maintain constant the energy radiated per unit length. Each antenna terminates in an impedance element Z which is designed to absorb the residual unradiated energy reaching the remote terminal.

Figure 15 illustrates a section of an antenna circuit loaded for waves of two different frequencies. L_2 and C_2 indicate respective series inductance including the natural inductance of the circuit and series capacity which together give a capacity reactance at one of the desired frequencies. The shunt path L_3 C_3 C_1 does not affect current of this desired frequency, since L_3 and C_3 constitute an antiresonant loop having substantially infinite impedance at that one frequency. The shunt path may, therefore, be regarded as open for the frequency considered. For current of a second frequency, the path L_3 C_3 is conductive and the net reactance of the whole unit at this frequency may be varied by varying C_1 so as to give any reactance desired for the recond frequency current. Of course, an additional shunt path such as L_3 C_3 C_1 could be used for another frequency by shunting such a path about condenser C_1 and including in it a tuned loop or antiresonant circuit to exclude current of the second frequency. In this manner, the number of different frequency currents may be increased as much as desired.

Figure 16 represents a circuit having two

nating impedance connected thereto for absorbing, without reflection, energy transmitted to said impedance.

9. In a directive radio transmitting system in combination, a transmitting antenna, a source associated therewith for supplying continuous waves to said antenna and a terminating element connected to said antenna for preventing reflection of said waves back toward said source.

10. In a directive radio transmitting system in combination, a transmitting antenna, means for supplying periodic energy thereto, said antenna being so loaded as to transmit the wave form of said energy at a velocity exceeding that of light and a terminating impedance connected to said antenna to prevent retransmission of energy back to said means.

11. In combination, a long horizontal antenna, a source of periodic energy associated therewith for supplying energy thereto, and means for causing said antenna to radiate a uniform quantity of the supplied energy per unit length of the antenna.

12. In combination, a long antenna, means connected to one terminal thereof for supplying periodic energy thereto, and means for changing the radiation resistance of said antenna progressively throughout its length so as to keep the quantity of radiated energy constant per unit length.

13. An antenna, means for supplying a periodic wave of a given frequency thereto and means for progressively varying the wave propagation velocity of said antenna whereby the radiated energy of said wave may be directively focussed upon a distant point.

14. A conductor curved upwardly throughout its length, and means for so loading said conductor as to cause it to radiate energy directively throughout its length.

15. A method of directive radio transmission, utilizing a source of carrier waves and a linear radiating conductor connected therewith, which comprises the steps of radiating a portion of the waves of said source into space, transmitting another portion of said waves along the conductor, absorbing a portion of the energy thus transmitted at points in the conductor, radiating the absorbed energy from said points, neutralizing the radiation from said conductor in one direction, and preventing deflection of the unabsorbed transmitted waves at the remote terminal.

16. The method which comprises propagating an electric wave along a linear conductor at a wave propagation velocity exceeding that of light, radiating a substantially uniform amount of wave energy from each unit length of said conductor, and neutralizing the radiation from said conductor in one direction.

17. The method of directive radio transmission, utilizing a conducting element, which comprises propagating said waves along the conducting element, causing the propagated velocity to differ in a systematic manner at different points in said conducting element, absorbing a portion of the energy from the wave propagated thereacross at each element of the conducting element, radiating said absorbed energy, and neutralizing the radiation from said conducting element in one direction.

18. The method of directive transmission comprising propagating waves along a conductor at a velocity exceeding that of light, progressively varying the velocity of propagation throughout the length of the conductor, and neutralizing the radiation from the conductor in one direction.

19. A loaded circuit having loading reactances progressively varying in magnitude throughout its length so as to vary the wave propagation velocity for waves of a given frequency, whereby said circuit tends to radiate directively in lateral directions, and means for neutralizing the radiation in one of said directions.

20. A directive transmitting antenna comprising a loaded circuit having its loading constants so adjusted that waves of a given frequency are propagated thereover at a velocity exceeding that of light, whereby said circuit tends to radiate directively in lateral directions, a terminating impedance connected to said circuit for absorbing, without reflection, energy transmitted to said impedance, and means for neutralizing the radiation in one of said directions.

21. A loaded circuit having loading reactances progressively varying in magnitude through its length so as to vary the wave propagation velocity for waves of a given frequency, whereby said circuit tends to radiate directively in lateral directions, and means for neutralizing the radiation in one of said directions, said means comprising a second loaded circuit arranged in parallel with the first loaded circuit.

22. In combination, a source of energy and connected thereto a loaded circuit having loading reactances progressively varying in magnitude throughout its length so as to vary the wave propagation velocity for waves of a given frequency, whereby said loaded circuit tends to radiate directively in lateral directions, and means for neutralizing the radiation in one of said directions, said means comprising a second loaded circuit arranged in parallel with the first loaded circuit with respect to said source and including a phase shifting means, whereby the energies supplied to said loaded circuits have a desired phase difference.

In witness whereof, I hereunto subscribe my name this 13th day of May A. D., 1921.

RAYMOND A. HEISING.

degrees of freedom and which can be adjusted to give the same desired reactances as are given by the arrangement of Fig. 15. This circuit may accordingly replace that of Fig. 15. Its exact adjustment is, however, considerably more difficult.

Figure 17 illustrates an adaptation of the principle of Figure 15 applied to shunt inductance loading. L_5 represents a unit shunt loading inductance designed in accordance with the principles previously laid down for currents of one given frequency. The antiresonant loop 35 tuned to this one frequency effectively cuts off the other shunt paths for such currents. The loop 35 admits currents of the second frequency and a variable inductance L_6 permits the network L_5, 35, L_6 to give the proper inductive reactance for the second frequency current. Loop 36 in the third path is antiresonant to and effectively excludes currents of the second given frequency for which variable inductance L_6 provides the desired reactance. It conducts a third frequency for which L_7 together with the rest of the network may determine the desired reactance.

Figure 18 illustrates a receiving system with progressively changing loading elements. The conventional receiving element is coupled to the antenna in the ordinary manner and is preferably designed to introduce therein the proper terminating resistance to avoid reflection loss in accordance with the principle previously stated.

Figure 19 shows a multiplex transmitting system equipped with three carrier wave sources and an antenna loaded in the manner of Figure 17. Transmitting keys are associated with two of the sources and a microphone with the third, but it is to be understood that these are merely representative of any desired arrangements for modification of the carrier waves.

Throughout the specification the various features of the invention have been explained from the standpoint of radiation at a transmission station. The principles of wave absorption are in general the same as those of wave radiation. It is, therefore, to be understood that the various features of the invention are equally applicable to receiving systems and the various circuit diagrams may each be considered as representations of a receiving system with the simple substitution of receiving apparatus for the carrier wave source.

In the appended claims the transfer of energy either by radiation from an antenna to the ether or by absorption from the ether to the antenna is analogous to the transfer of energy between media of different characteristics. In telephone parlance the term "transducing" is commonly used to describe generally a transfer of energy without limitation as to the nature of the transfer. Wherever this term occurs in the appended claims, it will be understood that it is intended to be generic both to radiation and absorption of wave energy as well as to the transfer generally of energy from a medium of certain characteristics to media of different characteristics.

What is claimed is:

1. A method of directive radio transmission, utilizing a source of carrier waves and a linear radiating conductor connected therewith, which comprises the steps of radiating a portion of the waves from said source into space, transmitting another portion of said waves along the conductor, absorbing a portion of the energy thus transmitted at points in the conductor, radiating the absorbed energy from said points and preventing reflection of the unabsorbed transmitted waves at the remote terminal.

2. The method of wave transmission which comprises radiating from a conductor very long with respect to the wave length of the radiating energy an amount of energy per unit length of said conductor substantially uniform throughout the entire length of said conductor.

3. The method which comprises propagating an electric wave along a linear conductor at a wave propagation velocity exceeding that of light and radiating a substantially uniform amount of wave energy from each unit length of said conductor.

4. The method of directive radio transmission, utilizing a conducting element, which comprises propagating said waves along the conductor, causing the propagated velocity to differ in a systematic manner at different points in said conducting element, absorbing a portion of the energy from the wave propagated thereacross at each element of the conductor, and radiating said absorbed energy.

5. The method of directive transmissi comprising propagating waves along a c ductor at a velocity exceeding that of li and progressively varying the velocity o propagation throughout the length of the conductor.

6. The method of electric wave transmission, using a long conductor, which comprises supplying periodic energy to said conductor and propagating it at progressively increasing velocities throughout the length of the conductor.

7. A loaded circuit having loading reactances progressively varying in magnitude throughout its length so as to vary the wave propagation velocity for waves of a given frequency.

8. A directive transmitting antenna comprising a loaded circuit having its loading constants so adjusted that waves of a given frequency are propagated thereover at a velocity exceeding that of light and a termi-

Patented Dec. 24, 1929 1,740,950

UNITED STATES PATENT OFFICE

ALEXANDER MEISSNER, OF BERLIN, GERMANY, ASSIGNOR TO GESELLSCHAFT FÜR DRAHTLOSE TELEGRAPHIE M. B. H. OF BERLIN, GERMANY, A CORPORATION OF GERMANY

DIRECTIONAL ANTENNA SYSTEM

Application filed July 15, 1925, Serial No. 43,684, and in Germany July 25, 1924.

This invention is particularly adapted for the purpose of transmitting intelligence through space, especially by the use of short electromagnetic waves, as it is now well known that antennæ capable of such transmission will produce strong radiation with the result that signals therefrom may be received at receiving stations at comparatively great distances away. In order to accomplish this object, aerials are located at a comparatively great distance from the ground, and are of considerable length or, on the other hand, grounded aerials of comparatively great vertical height are so excited or energized that they will oscillate on a wave length that is proportioned to the length of the antenna as one is to three-quarters or else as one is to a whole multiple of the wave length plus one-quarter of the wave length. Such a radiating antenna is usually attached at its upper end to a tall mast or tower from which it is insulated and which tower is also insulated from the earth.

Where it is desired that a directional action of the radiation may be produced, reflecting auxiliary antennæ are employed which may be arranged in a special form such as in a form having conductors in a parabolic surface, which surface may surround or properly enclose the transmitting or receiving antenna, as the case may be. Furthermore, reflecting actions are produced if conducting surfaces of bodies are located in the vicinity of the radiating or transmitting antenna above mentioned.

The object of the present invention is to utilize the tower carrying the radiating aerial in such a manner that it acts as a reflector for the short waves emitted by said transmitting aerial. Such towers are obviously made of conductive material, such as steel, and are capable of having a natural period of oscillation. In order to control the period of oscillation, the said mast or tower can be given the requisite shape to embody the electrical constants which will cause it to oscillate at the desired period of oscillation or wave length. In order to produce a definite directive effect a certain angle of phase displacement must exist between the oscillations of the aerial and the oscillations of the reflecting means which, in the present instance, is the supporting tower. This phase displacement, under certain conditions, requires means for adjusting the period of oscillation of the tower to correspond with and effect the necessary relation with the oscillations induced therein by the transmitting aerial. According to the present invention such tuning means are provided as a part of the tower structure or are connected therewith and with a ground connection preferably through a variable reactance.

One form of the invention is illustrated in the accompanying drawing in which the letter A indicates the radiating aerial which, as indicated by the dotted line, has a length such that it oscillates on a wave length which is one and one-quarter the length of the transmitting wave. The aerial A is attached to the top of the supporting tower or mast M from which it is insulated as indicated. This mast is constructed of conductive material and at the bottom rests on an insulator J. For the purpose of tuning said supporting tower to the proper period it is grounded through a reactance W consisting of an induction coil and condenser, said reactance being made variable as indicated.

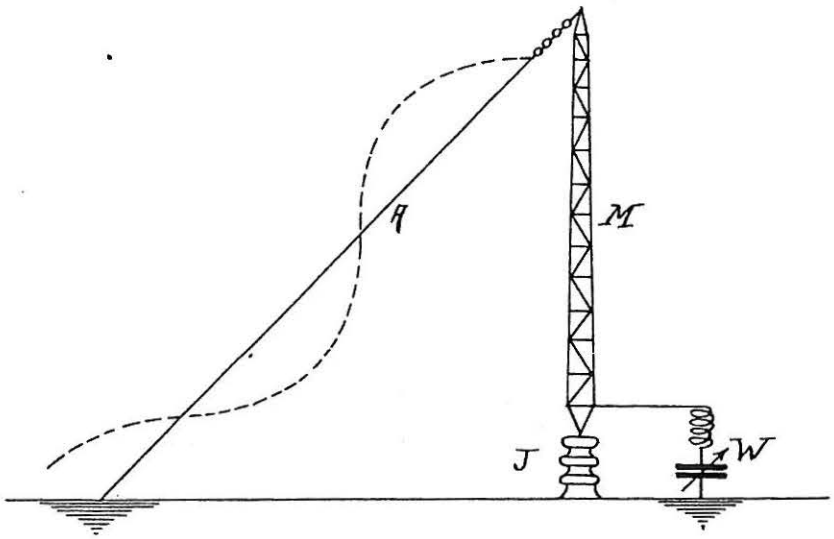
Having thus described this form of my invention what I claim and desire to protect by Letters Patent is:

1. A directional antenna system comprising an aerial, a conductive support therefor, a tunable circuit between said support and the ground for proportioning the electrical characteristics of said support so as to reflect the oscillations induced therein by the oscillations generated in the aerial at a desired

Dec. 24, 1929. A. MEISSNER 1,740,950

DIRECTIONAL ANTENNA SYSTEM

Filed July 15, 1925



Inventor
Alexander Meissner
By his Attorney
Ira J Adams

wave length, whereby the aerial is given a directional characteristic.

2. A directional antenna system comprising an aerial, a conductive support therefor, said support being insulated from said aerial and from the ground and tuning means forming a path for high frequency currents between said support and the ground, whereby the aerial, by virtue of absorption and reflection by the support, of electromagnetic energy radiated from the aerial, is given a directional characteristic.

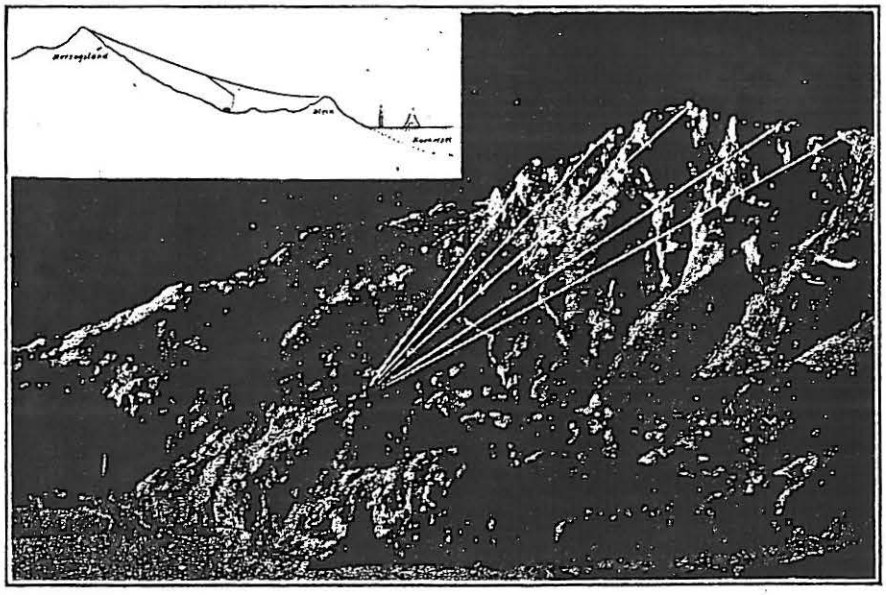
Signed at Berlin, Germany, this 23rd day of June, 1925.

ALEXANDER MEISSNER.

A HIGH POWER WIRELESS STATION WITHOUT MASTS.

A NEW high power wireless station is under construction between Kochel and Walchen in the south of Munich.

Taking into account the fact that the costs for the construction of the antennæ masts represent by far the largest expenditure for the equipment of a high power station, the engineers have tried to make use of the natural altitudes in the mountains for this purpose. The Herzogstand, with a height of 1,732 metres, situated in the north-west of the Walchen Lake, is very precipitous towards the north. In an easterly distance of 2·6 kilometres the ground rises to a height of 940 metres at the Kochel Lake. Between these two points there is rather swampy ground—the Jochbach Dale—in which the station has been erected, for here in this valley are the most favourable primary conditions for the earthing equipment. Referring to the illustration, a rope has been placed between the Herzogstand and the "Stone," at the very middle of which, namely, at an equal distance of 1,300 metres, the supply main to the station is fastened. In order to guard against the rope breaking when subjected to hoar-frost or to the pressure of the wind, provision has been made at the Stone for a special device which balances the large stresses in the rope. The rope is insulated, led over a roller, and fastened to a trolley which is running on rails over an inclined plane. This trolley is loaded to such an extent as to keep the rope sufficiently taut when subjected to normal tension. Under the effects of wind or hoar-frost, known to sometimes produce considerable strains, the rope slackens down as the trolley gives way.



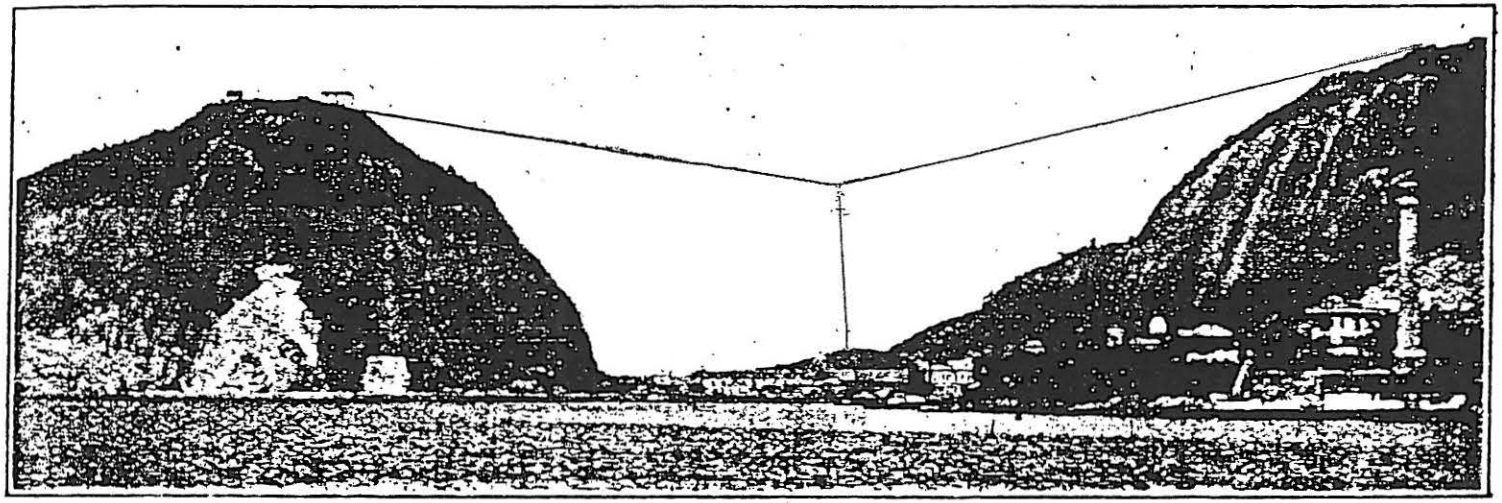
Illustrating the antennæ system of a new high power wireless station under construction between Kochel and Walchen, in the south of Munich.



The illustration indicates at the right-hand over the level of water the heights of the Eiffel Tower and the Nauen Station, so that it is quite evident what great economy is made with regard to the height of antennæ by the construction and utilisation of mountain antennæ.

Extensive measurements made have proved that especially with one type of antenna (the so-called "L" antenna), very good results have been obtained. It has also been proved that large stations can be constructed without the use of masts, but making use of the different altitudes of the mountains. With the use of a high voltage for the antennæ, even larger ranges may be obtained than those produced by the usual type of station. One rope alone is, however, not sufficient for a large station of this sort, but several ropes, about four or five, are needed. Their arrangement can be seen in the photograph. The whole aerial equipment has a span of more than 2½ kilometres, and a free height of about 300 metres. The easy accessibility of the top of the Herzogstand represented a great advantage. A highway makes good communication with the staff quarters erected at an altitude of 1,575 metres. Another decisive factor in the choice of the site for the radio station was the vicinity of the huge power station of Walchen Lake, which is said to have an average output of 168,000 h.p., and which can easily supply a main wireless station with sufficient power without impairing its general current output. The power station obtains its power from a 200-metres fall of water. Such a power station is well able to supply energy much more cheaply than works making use of coal for the generation of electricity.

It is intended to equip the station with a Lorenz-Poulsen generator of about 2,000 Kw., as well as with a Lorenz high frequency machine of the same output. The production of high frequency currents by machines will be effected directly or by means of a frequency transformer. Thus either system may be used, according to the needs of the moment. With this arrangement there is the possibility of making use of long wavelengths for very long distance transmissions, and on the other hand, of using shorter wavelengths for short distance transmissions.



The imposing aerial system of the Brazilian radiophone station of "Praia Vermellia" at Rio. The cage antenna is 330 feet high and is suspended from the Urca mountain (left) and the Babilonia mountain.

THE LEAFIELD IMPERIAL WIRELESS SERVICE*

By E. H. Shaughnessy, O.B.E., M.I.E.E.

THE Leafield station was originally planned in 1913, and it was to be a station of the spark type using 300 Kw. Owing to the outbreak of war, fortunately that form of construction did not develop. During the war there were marked developments in radio transmitting apparatus, but the most marked development of all was the development of the arc for high power. Before 1914 the biggest arc that had been made use of, I think I am safe in saying, was one of 100 Kw., and there were many 25 and 30 Kw. arcs developed during the war. Then, towards the end of the war, there were developments in the high frequency alternator. Apart from one alternator running in America, when we were designing the Leafield station there was no high frequency generator that had proved itself capable of dealing with 250 Kw. satisfactorily, except the improved design of Poulsen arc, which had proved itself quite satisfactory and had carried out satisfactory programmes. I personally visited the biggest arc stations on the Continent and saw the first Latour high-frequency alternator running in France, but quite apart from seeing these things and spending some time observing their working, there is a much better way of determining the commercial efficiency of any generator, and that is by establishing a watching station and putting expert telegraphists there to take down the whole of the traffic and analyse the whole of the traffic at that station. We did this, and our opinions that the arc is the best and most suitable generator for high power work were confirmed.

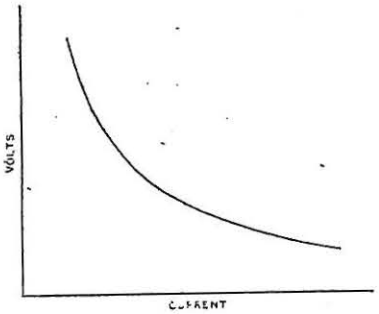


Fig. 1. Characteristic curve of the arc.

Perhaps this evening I can assume that most of you, at any rate, are mainly conversant with the receiving side, and that therefore I shall be justified in giving you some idea of the principle on which the arc works.

In the first place the ordinary arc was studied and it was found that it behaved in a very peculiar manner—that the arc did not obey Ohm's law.

If you look at the curve of Fig. 1 you will observe that the lower line indicates current and the vertical part indicates volts applied at the terminals. The interesting part of this curve is that when you have low volts at the terminals you have a big current; when the current passing through the arc diminishes you have an increase of potential across the arc. In other words, we say the arc has a negative characteristic. The smaller the current flowing through the arc, the larger is the potential difference across the arc. Duddell considered this negative characteristic, and concluded that it could be used

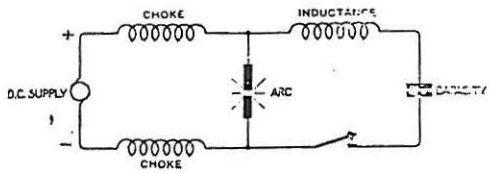


Fig. 2. An oscillatory circuit.

to produce oscillations. He took an ordinary arc and joined across the terminals an inductance and capacity (Fig. 2), and fed the arc with a direct current supply. Let us assume that we put a direct current supply through the arc, and then we join up the wire connecting the arc to the condenser and inductance. The first effect of joining up this circuit will be to cause the condenser to suck current from the path through the arc into the condenser path, thus making the current going through the arc smaller. The result of making that current smaller is to make the potential difference across the arc, and thus the potential difference across the condenser larger than it was, with the result that the condenser can be charged a little more, and this process goes on until we charge the condenser up fully and until the current through the arc is reduced to a very small amount. When you attain that stage no more current will flow into the arc, and as you have a conducting path through the arc, the condenser will now discharge back through the arc. By properly balancing the inductances, or by properly valuing the capacity and inductance you can produce oscillations. But such oscillations as Duddell produced are oscillations of audible frequency, and are therefore unsuitable for high frequency oscillations for wireless work.

Poulsen studied this subject, but he did not get to his final type of Poulsen arc immediately. He

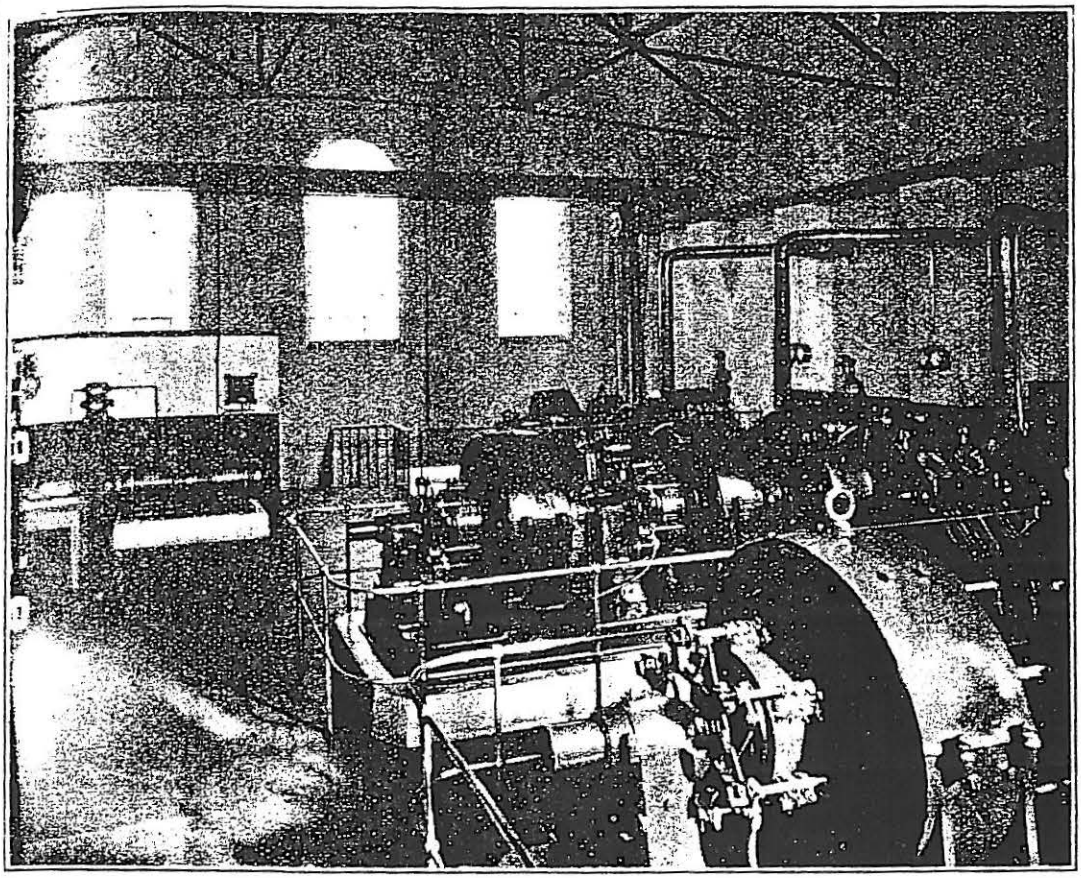
* Paper read before the Radio Society of Great Britain on Wednesday, November 28th, 1923.

[illegible] which is not supposed to be on any of these wavelengths: but the harmonics have a characteristic tonic train note.

Then I was very much interested in a statement I saw in one of the popular journals that come out weekly—not the journal of this Society. It said that Northolt is not very much bother now because the Post Office had put valves in, and he supposed that some day or other we should have valves at Leafield. That seems to indicate that valves do not produce harmonics. Do not be misled. There is no greater fallacy. We did put in valves at Northolt, and we have valves at Northolt. It is very interesting to know that when we put in arcs at Northolt we were told by some very wise people that we were very archaic to put them in, and that if we had put in valves there would have been no harmonics. We developed the arcs at Northolt, and put in a coupled circuit, and there is no doubt about it that the coupled circuit at Northolt is very satisfactory both from the working point of view and from the marked reduction in undesirable emissions. If you live next to the aerial of any high power station you will have some trouble, but we worked on these coupled circuits for some time, giving reasonable satisfaction to the stations with which the arcs originally interfered. Then one day we got our valves going with a little more current into the aerial, but we were promptly told that we had gone back to the plain aerial arc again and were causing more disturbance than ever.

To get back to Leafield, we have tried various means of reducing the mush and the harmonics there. We have coated one of the carbons used there with a silica paint, but it has not produced very much effect. Then we have tried water cooling of the carbon in the same way as we water cool the copper electrode, the idea being that as the arc rises up between the electrodes it will strike the cool surface at the same instant every time, and we shall get regular kicks or regular impulses into our aerial, and thus get a reduction in the harmonics.

I have got a sample mast stay insulator on the table. That is a stay insulator after it has been in



The engine room at Leafield.

have been tested to about 20,000 volts insulation. They are capable of adjustment between 500 volts and 1,000 volts for the two machines in series. In addition, we have two 60 Kw. turbo-generators which are used for lighting purposes, providing power for circulating water for the condensers; also for working the pumps, for circulating water for the arcs; the pumps for the air compressors for working the pneumatic high speed keys and blowing out the sparks at the keys.

In Fig. 3 are shown choke coils leading from the generator to the arc. In practice these choke coils are about 6 ft. high and made to carry 500 amperes.

The Elwell Poulsen arcs at Leafield (Fig. 4) weigh about 7 tons. Each of the field magnet coils weigh 30 cwt., and they are supported on a concrete tile-lined base by means of the supports at the ends. The field magnet coils are on one of the parts of the field magnet which continues below the base, the pole pieces project into the arc chamber. The latter is fed by means of these lubricating vessels with methylated spirit. The arc chamber itself is water-cooled on all its faces. You can see the rubber tube which directs the water into the jacket of the arc chamber. The anode is water-cooled right up to the tip, and the anode insulator keeps the copper electrode insulated from the body of the arc. All the other metal parts of the arc are connected together.

It is rather interesting to observe that the arc is worked between 600 volts and 900 volts. A lot of care is taken to put in a good anode insulator, and then they are connected together with a water column. The water column is, however, of very high resistance so that even if we get a small current flowing through the water it does not affect the working. But it is important that we should have a good anode insulator.

One of our troubles was this anode insulator. We used a quartz insulator to begin with, but it was not unusual for some of these insulators to go in seven or eight hours, and they were very expensive things. We have got over the trouble now, and we use an outer insulator such as you see, and another insulator is put inside it which

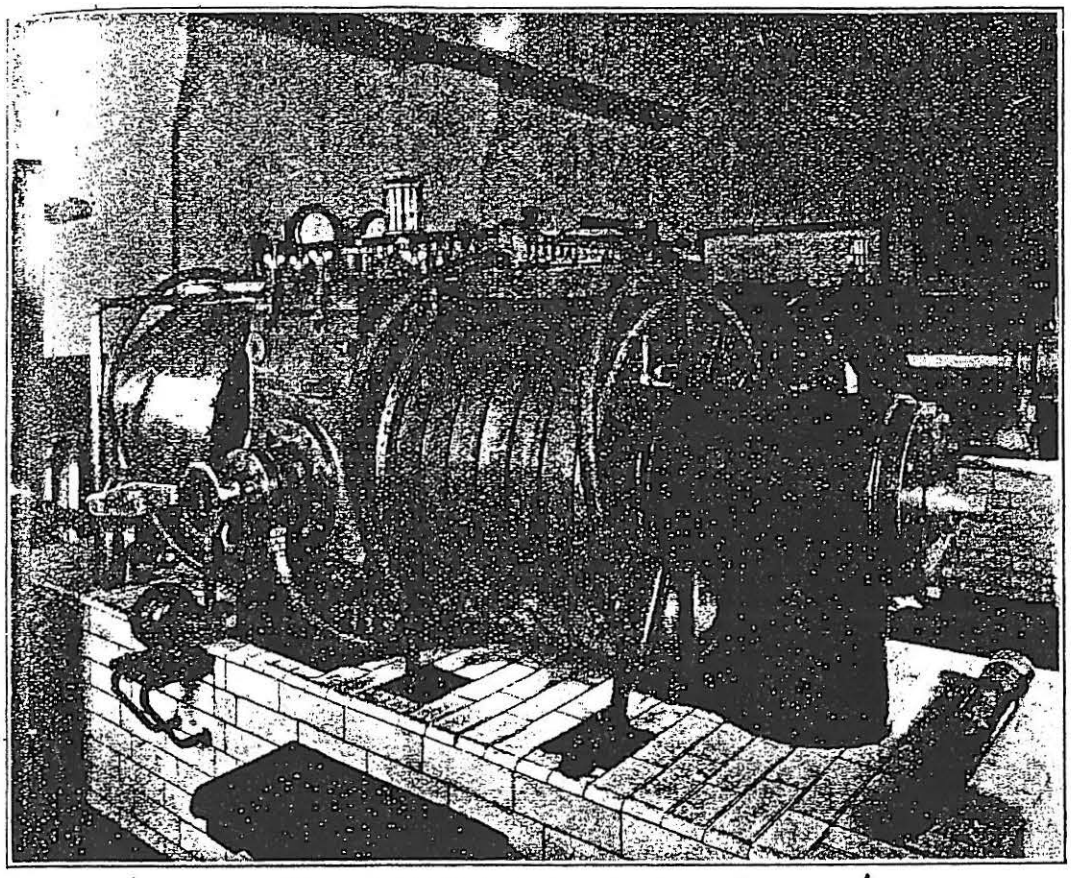


Fig. 4. Leafield Wireless Station 250 Kw. arc.

covers the copper electrode that goes right inside the arc chamber; the space between the two is filled with asbestos rope. By that means we are now using insulators which cost very little, and last a very long time. The cost of these has come down to a negligible quantity.

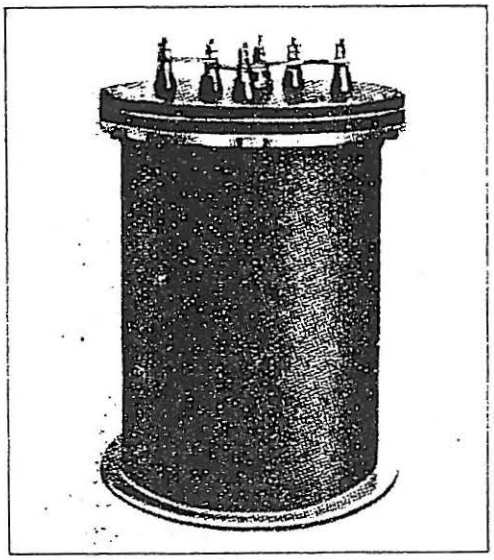


Fig. 5. Oil immersed condenser.

If you start up an arc after it has been cooled down for a little while you find that the old gases, or some of them, are still there, and the air gets in through the lid and the crevices, with the result that when you start an arc by pushing the carbon up against the copper, you also start a very loud explosion. We have had the lid of the air chamber blown off.

We have extended the bolts that hold the lid on and fitted longer springs to take any upward pressure when the lid is lifted by an explosion. A better method of getting over the trouble, we have found, is to let the arc cool down and before starting it up again to blow through the arc with dry air. In that way you can clear the old gases right away, and it is possible to start up with the methylated spirit without trouble from explosion.

Fig. 5. shows one of the oil immersed condensers.

Fig. 6 is a choke coil. The loading inductance at Leafield has 22 turns, and is 12 feet in diameter. The coil is designed to carry a heavy current, and when we started working at Leafield we had trouble with the supports of this coil. We got 190 amperes in it, and after working for a little while we found that smoke was issuing from the side columns. The column was punctured, and it was found that the paxolin rods inside the porcelain reels of the columns could not stand up to the high frequency effect. We got over the trouble by building a wooden spider over the top of the inductance coil.

I am sure you would not like me to finish Leafield without saying something about the harmonics. As a matter of interest we have taken very careful measurements of the strength of the harmonics at Leafield, and of the fundamental value, and we find that when we are radiating with 190 amperes in the aerial we actually radiate on the fundamental 4 Kw. approximately, and the value of the second harmonic is 0·0002 Kw. That is a very insignificant fraction of the total radiated energy. It should be realised that a very small fraction of 200 Kw. input when using 300 ft. masts will give you signals over a fairly large area. When Leafield was first started there was a lot of work to be done in order to get it into proper trim. We had to find out exactly the best field strength, the best adjustment of the arc length and the best mixture in the arc chamber to suit the particular arcs and the particular loads. The same field strength does not do for all wavelengths. These things can only be determined by experience, and I think that our Leafield arcs are now tuned to such a condition that they are at least equal to any other.

With regard to harmonics, I read in the paper the other day that G.B.L. meant "God Bless Leafield." I am sure we feel that we have been blessed on very many occasions. (Laughter.) There has been a lot of bad shouting about Leafield, and whenever anybody gets any harmonics it is always Leafield. (Renewed laughter.) That is, of course, due to one or two things, and mainly to ignorance. I am out to be shot at after the paper, and to answer questions —(Laughter) —but the first thing to remember is that unless one is a very good operator and can read Morse it is impossible to say what station is causing

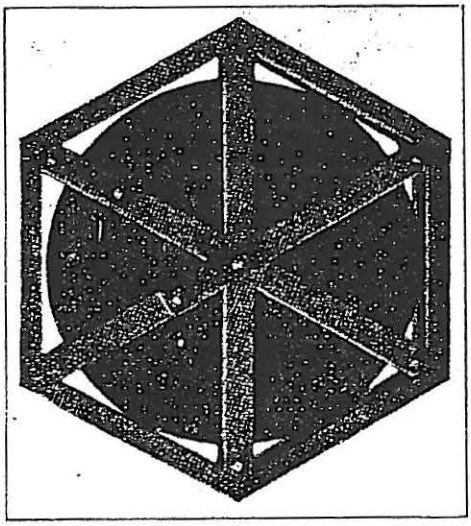


Fig. 6. Choke coil.

the harmonics. I daresay we get credit for all harmonics, including the valve continuous wave stations. I live at Tulse Hill, about six miles from Kidbrook, and I can get Kidbrook about eight times between 300 metres and 800 metres without heterodyning. That is a valve continuous wave

tried various arrangements with different electrodes, and burning the arc inside a chamber containing hydrocarbon gas and put a strong magnetic field across the arc. The effect of enclosing this arc in a chamber and using a gas, and also putting a strong magnetic field through, was to enable him to do two things—to get much higher frequencies from the arc, and also to get an arc which would deal with much higher powers.

Fig. 3 is the same as Fig. 2 except that we have now changed the oscillating circuit of inductance and condenser for an aerial. The capacity due to the aerial and the inductance in series with that capacity gives an oscillating circuit. The function of the two chokes is to keep the current supply to the arc constant. That is the simplest way of looking at it.

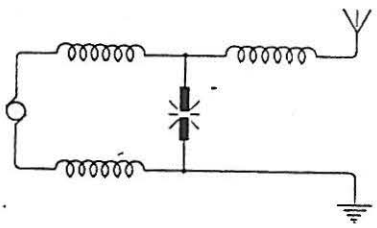
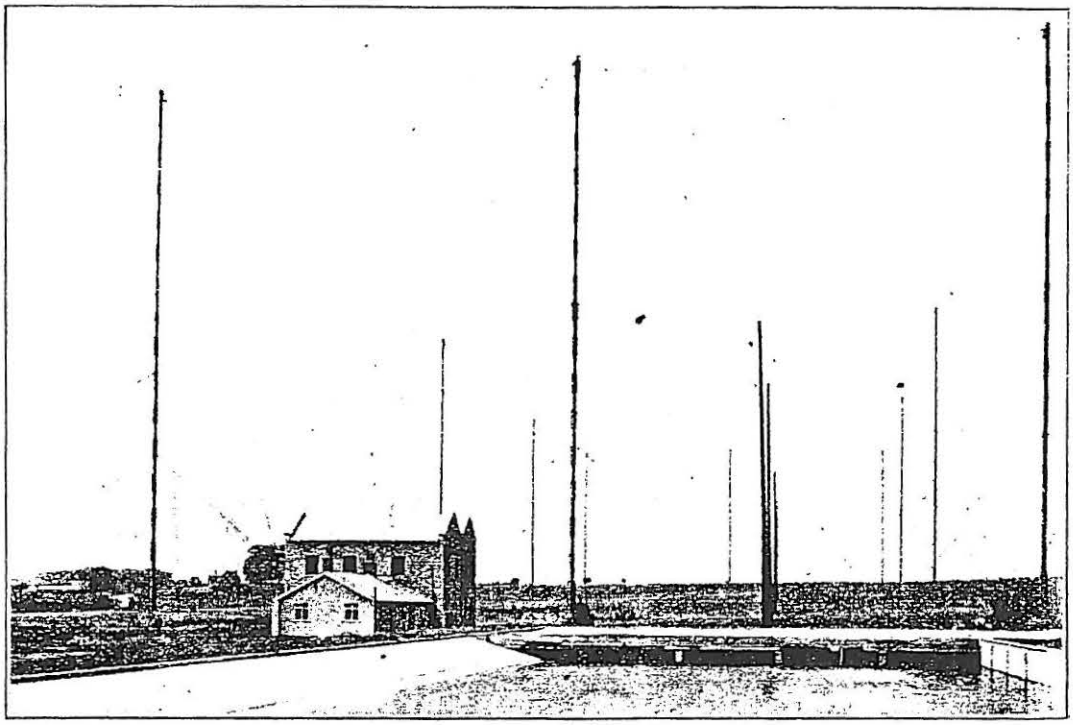


Fig. 3. Connections of arc to aerial.

use on the stays at Leafield for six months. The dielectric stresses in the body of the material have been so great that a very intense heat is developed and the porcelain disintegrates.

These are some of the troubles you get. It is not always the highest insulating material that is the most suitable for use in a high power wireless station.

There is another important point to realise with regard to the oscillating arc, and that is that it is possible to arrange the circuits—a bad arrangement of circuits—so that you can overcharge the aerial or condenser circuit, and actually reverse the direction of current in the arc, but the normal method of working the arc is to adjust the magnetic field, the arc length, and the hydrocarbon gas in such a manner that when the current, which is normally feeding in the arc, begins to flow into the aerial, it is entirely sucked out of the arc path, and the current through the arc just falls to zero immediately after the aerial begins to discharge through the arc. What you want to realise is that although you are getting oscillations in your aerial you are not getting alternations of current through the arc.



Wireless buildings, masts and cooling ponds.

Now we want to see how these things are brought into actual practice.

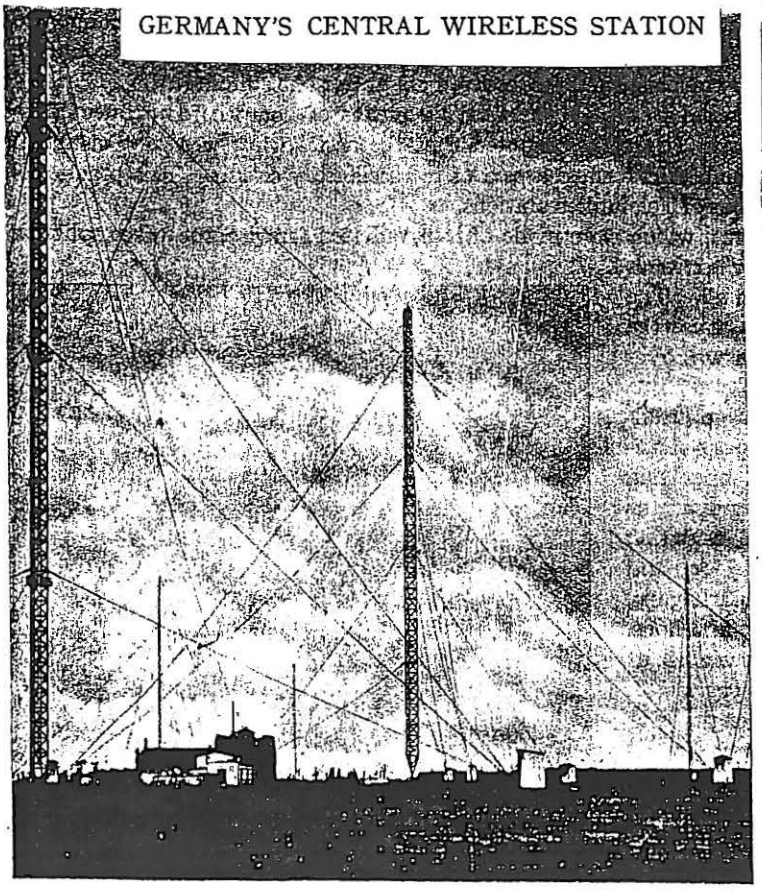
The main buildings of the station consist of the power house and the wireless building.

The boiler room has two boilers capable of evaporating 10,000 lbs. of water per hour, and in the next room we have our machinery; two turbo-generators of 250 Kw. capacity each, for the main supply to the arcs. These generators are rather special machines. We have the machines entirely insulated from the bedplates. Each unit consists of a turbine driving two machines off the same shaft, each machine being capable of giving 500 volts, the two being joined in series. The machines

I do not think there is anything else I want to say about the subject. I have tried to explain something about Leafield, and I shall feel very pleased if we have a discussion. I should like to acknowledge with thanks the loan of slides from Messrs. C. F. Elwell, Ltd.

(The Discussion following the reading of this paper will be published in a subsequent issue.)

GERMANY'S CENTRAL WIRELESS STATION



NAUEN. THE STATION BUILDINGS AND THE MASTS. THE 900 FOOT MAIN MAST IS SEEN IN THE CENTRE. IT IS SURROUNDED BY FIVE LESSER MASTS.

No less than 100 kw. was said to be delivered to the aerial, the antenna current being 120 amperes.

The illustration at the head of our article clearly shows the quenched spark transmitter at Nauen. The two heavily insulated leads from the transformer beneath the floor will be seen just to the left of the centre of the photograph, and the condenser (now consisting of copper and glass plates immersed in oil and no longer of the tubular type) will be seen behind them in the corner of the room. The four glass cases on insulating feet contain the numerous banks of quenched gaps, which are cooled by a strong blast of air. The large case against the further wall contains the jiggers, the single pole switches being used for changing the internal connections. A large aerial ammeter will be seen on the extreme left of the photograph, just below the decorative dado of painted inductances and condensers. Readers should also note the festooned wave forms supported by insulators painted on the wall. The receiving room is shown on page 920 and contains accommodation for a number of operators. The tall piece of apparatus on the right hand side of the window (not in the window itself) is a microphonic amplifier, which at one time was used with success to increase the strength of the received signals. It has now been replaced by a form of three electrode-valve, which acts both as a detector and amplifier.

Outside the buildings great changes have been made. First of all the 300 ft. mast was increased in height to 600 ft., but it had scarcely been completed when the whole structure crashed to the ground in a gale. Undeterred by this the engineers recommenced the work, and after many months of labour the new tower, nearly 1,000 ft. in height, was safely hauled into position A number of other towers were later erected, smaller than the central tower, but still very tall as masts go, and a new aerial of the double inverted-L type was erected. The new aerial, of course, required a much more extensive earth system than formerly, and many miles of wire are now embedded in the ground for conveying the high-frequency current to earth. The new central mast is of a similar construction to that first erected, and rests on a similar ball and socket. Our full page illustration gives some idea of the appearances of the masts and stays. The aerial wires, however, are too fine to be seen in such a photograph. In the distance can be seen the large station buildings and a good idea is obtained of the surrounding flat country.

Nevertheless, with this giant aerial and the high-power plant employed, Nauen has not been uniformly successful in its transatlantic work. On many occasions in bad conditions long-drawn out calls from POZ (Nauen) to WSL (Sayville) have vibrated through the ether without any answering call from the other side of the Atlantic. When conditions are favourable, however, and with the delicate amplifying receivers now in use, Nauen has been heard at very great distances, even on the west coast of America.

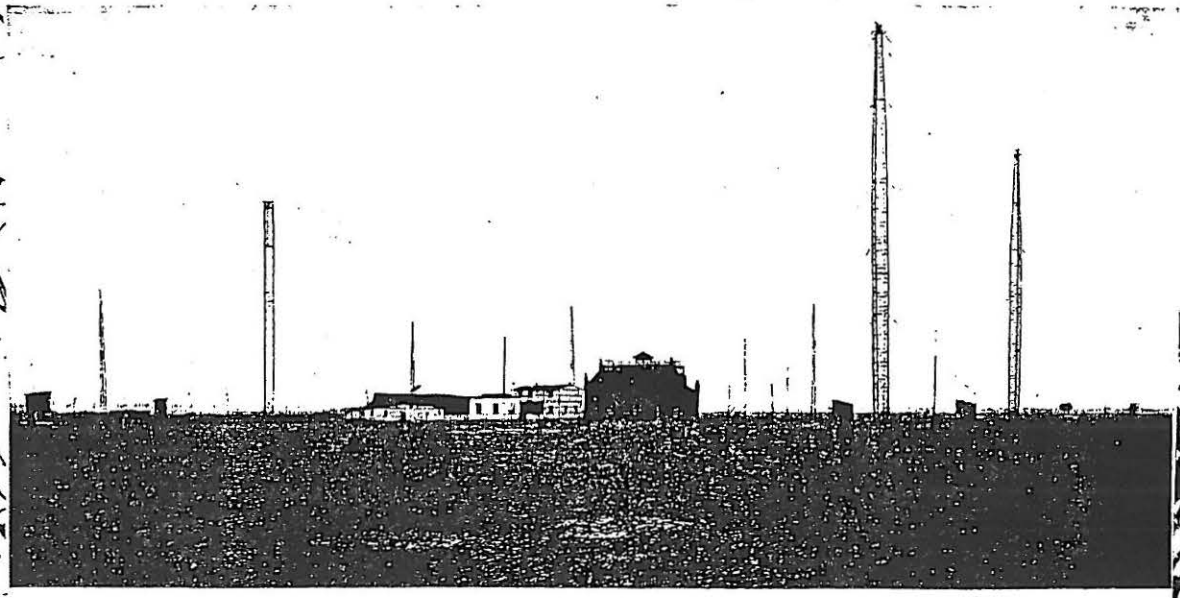


FIG. 148 *a*.—View of Nauen station.

[To face p. 204

The earthing arrangements were also improved. Owing to the marshy nature of the ground the new buildings were erected on a system of 200 iron piles, each of which was fitted with copper earthing plates rammed down into the ground water.

In the early spring of 1912 a severe storm, before the completion of the new plant, caused the upper 100 metre mast to fall, and during its fall it carried away one of the stays of the lower mast, causing the fall and destruction of the complete mast, but doing no damage to the station buildings.

At this time it was proposed to carry out experiments between Nauen and Togo in German S.W. Africa. For this reason the umbrella aerial was not rebuilt, but a directive aerial constructed. This aerial is shown in Figs. 148 *a* and *b*. It is supported by five towers each 120 metres in height, two of which serve to strain off the aerial proper.

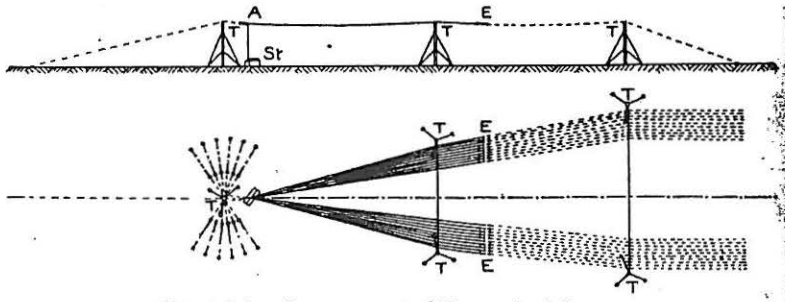


FIG. 148 *b*.—Arrangement of Nauen Aerial, 1914.

The single tower near the station is also equipped with an umbrella aerial for working with short wavelengths over comparatively small distances.

The equipment when completed, permitted an aerial radiation of 100 kw. and the station to attain a range of 9000 km. over Europe, Africa to off the coast of S. America, and for regular communication at night to be carried on between Nauen and Togo. Also, although propagation to the United States must be carried out with the aerial in the worst possible direction for this purpose, until Sayville was closed by the United States Government, daily communication was obtained. More recently, as already mentioned, it has been regularly received in Australia.

A high-frequency machine radiating 100 kw. was installed in 1913 for work with continuous waves and a wireless telephony transmitter, which in 1913 with 6 kw. radiation enabled con-

versations to be carried on from Nauen to Vienna, a distance of 400 miles.

The requisite enlargement of the high-frequency excitation circuit, in order to produce an antenna energy of 80 kw., necessitated a correspondingly increased source of primary energy.

It was not necessary to install new engines and dynamos as connection was obtained with the electricity works of the East Havelland district. The current is carried from here over a distance of 30 km. by means of overhead wires. The current is three-phase alternating current at a pressure of 15,000 volts. The last 400 metres of the connection consist of H.T. cable laid underground in order to avoid inductive disturbances from the aerial.

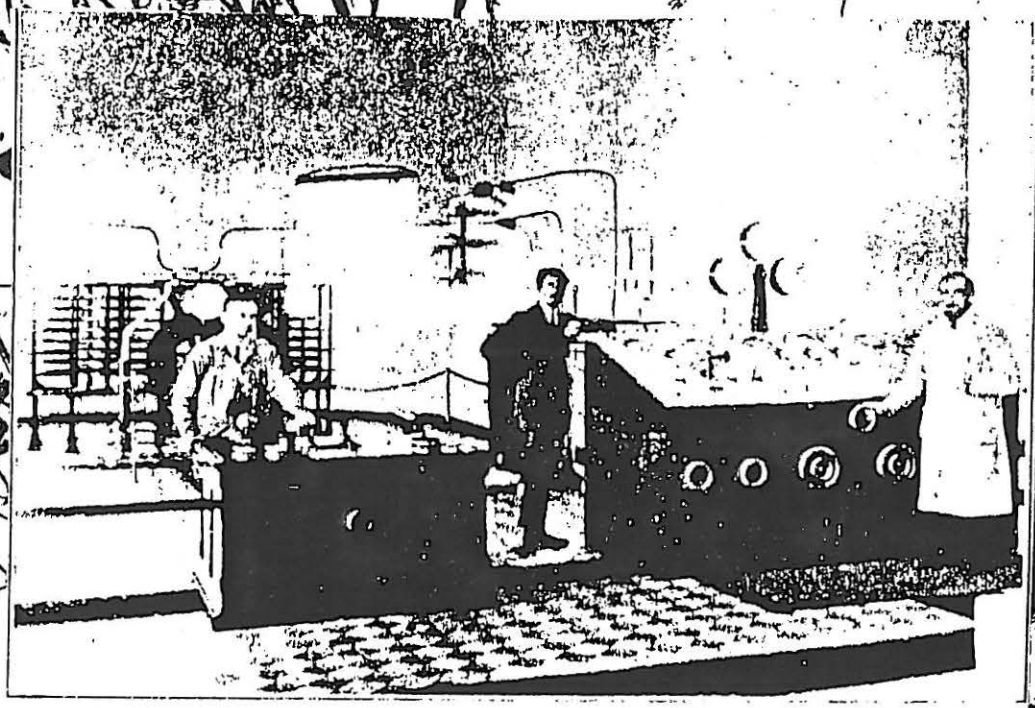
At the point where the overhead wires are joined to the underground cable, a switch station is situated, as the distributing system is carried out with double connections in case of breakdown.

The H.T. 15,000 volt three-phase current is transformed down after entering the wireless station and is subsequently converted into 220 volts continuous current.

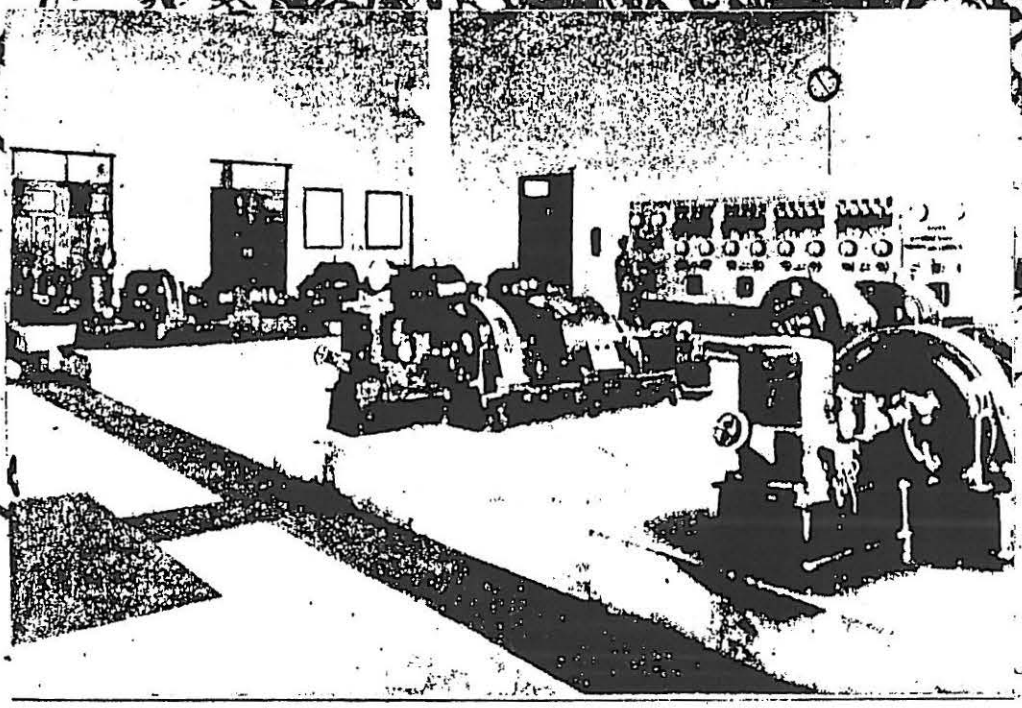
The plant comprises the requisite oil-filled transformers overload cut-outs, high-tension and lightning protective devices, the pressure and current measuring instruments, and the recording wattmeters and watthour meters. The plant is designed for an output of 300 to 350 kw. The whole plant is divided into two parts in order to gain the advantage of a certain reserve in case of breakdown, and to be able to work with half the total output when less energy is required.

Two three-phase transformers are installed, each for 150 kw. output. These give 120 volt three-phase current on the L.T. side. Two converters of single armature type each for 150 kw. output convert the three-phase current into continuous current at 220 volts. These converters can be connected either singly or together to the main bus-bars, from which the current is distributed.

In order to have a certain reserve of primary current, the existing steam generator set of about 100 h.p. is retained and an enlarged accumulator battery has been installed. These two sources of energy are sufficient even if the three-phase supply fails altogether to provide a continuous current supply of 80 to 90 kw. intermittently, and this is sufficient for short periods even for long distances.



Room from which the transmitter is controlled.



High Frequency Alternators.

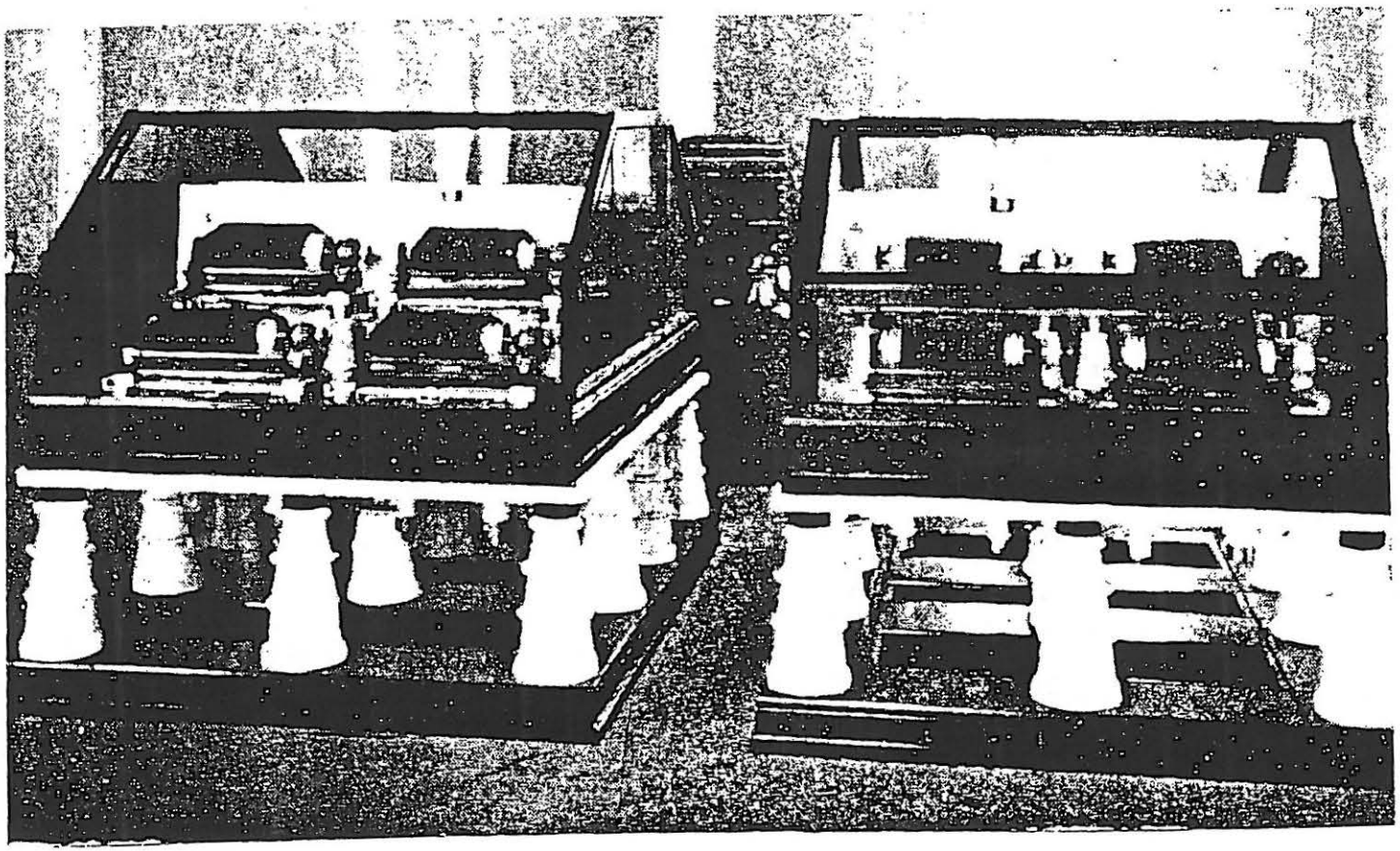


FIG. 152.—Spark gaps (Nauen).

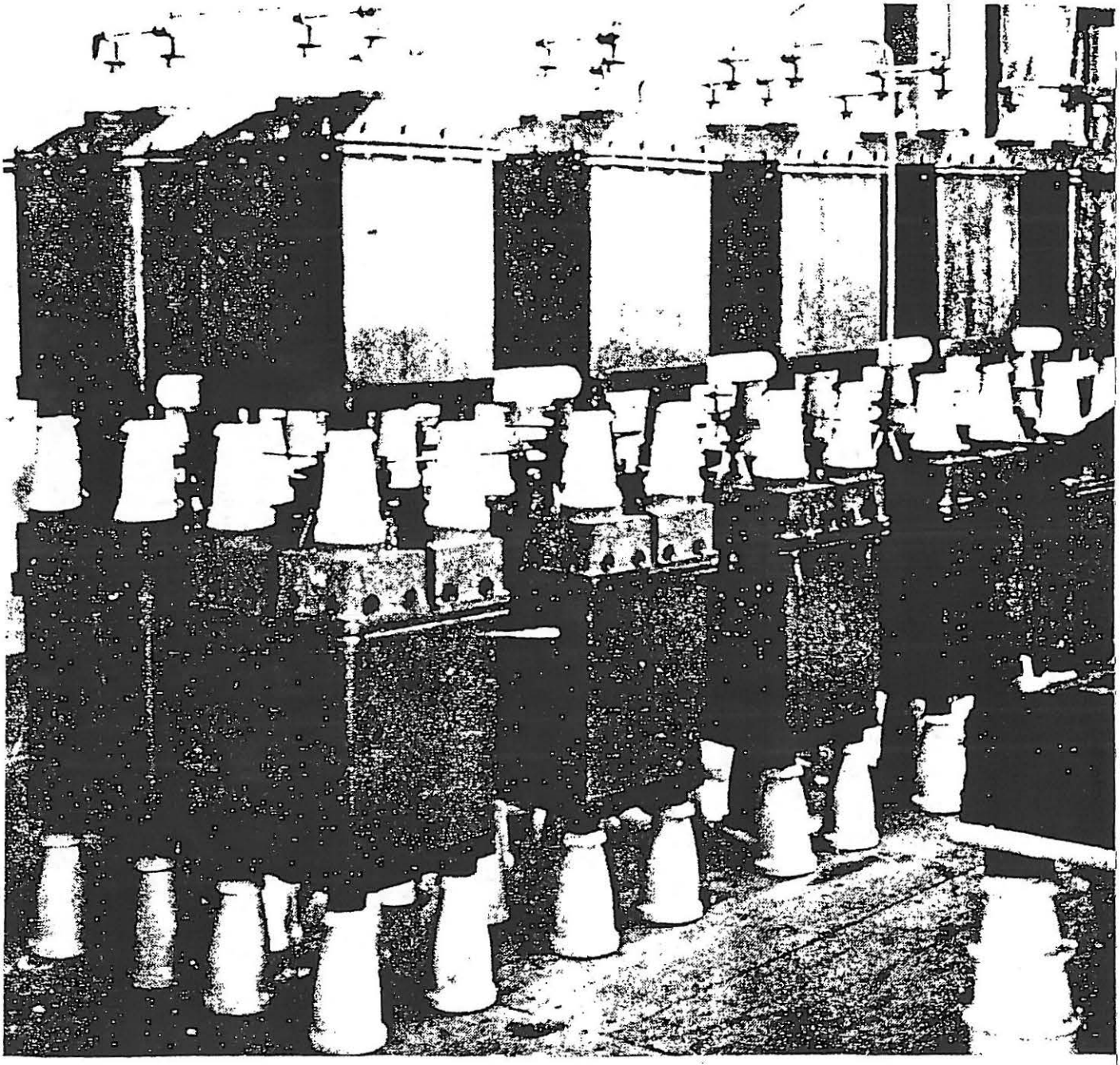


FIG. 151.—Condenser battery (Nauen).

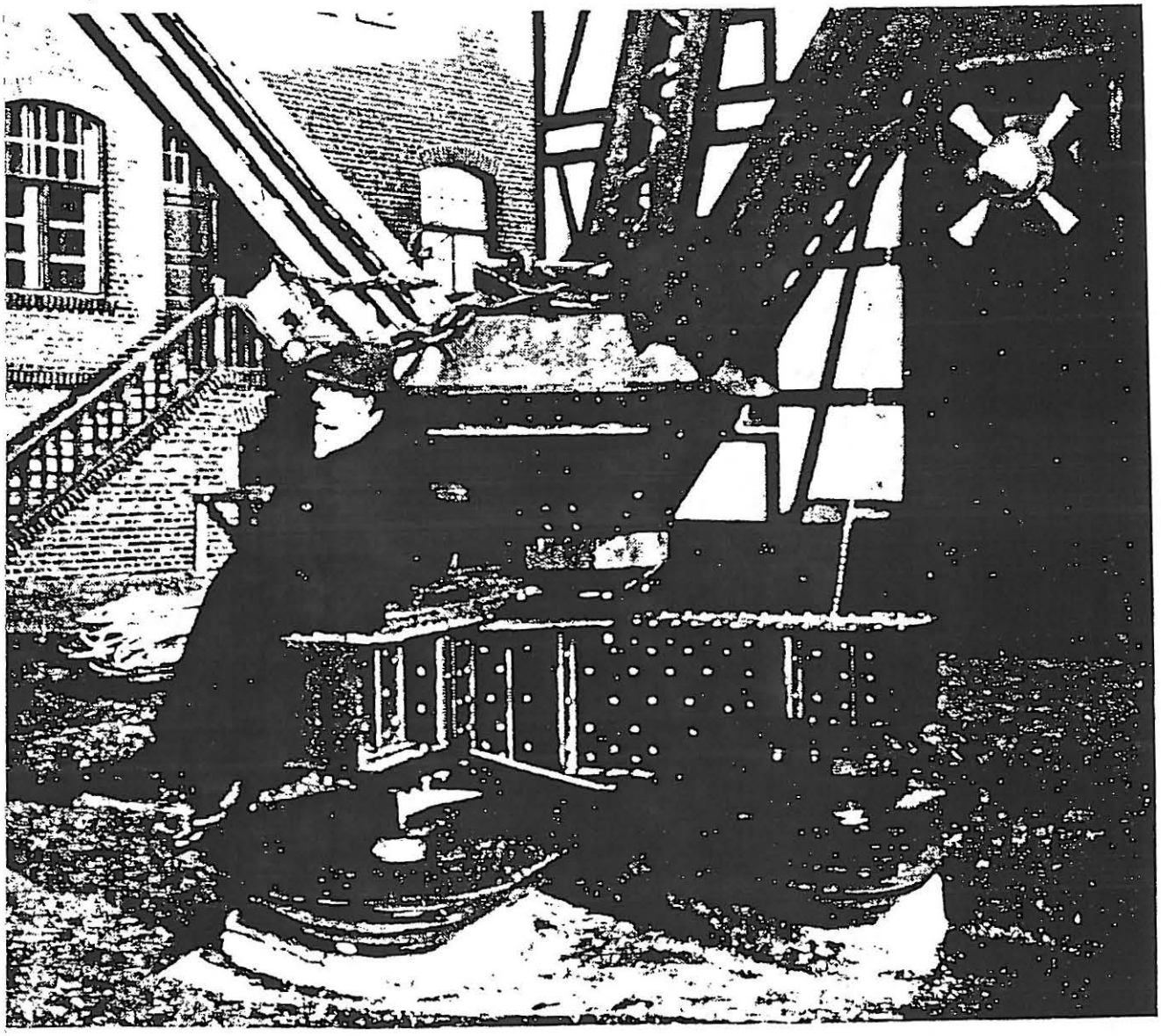
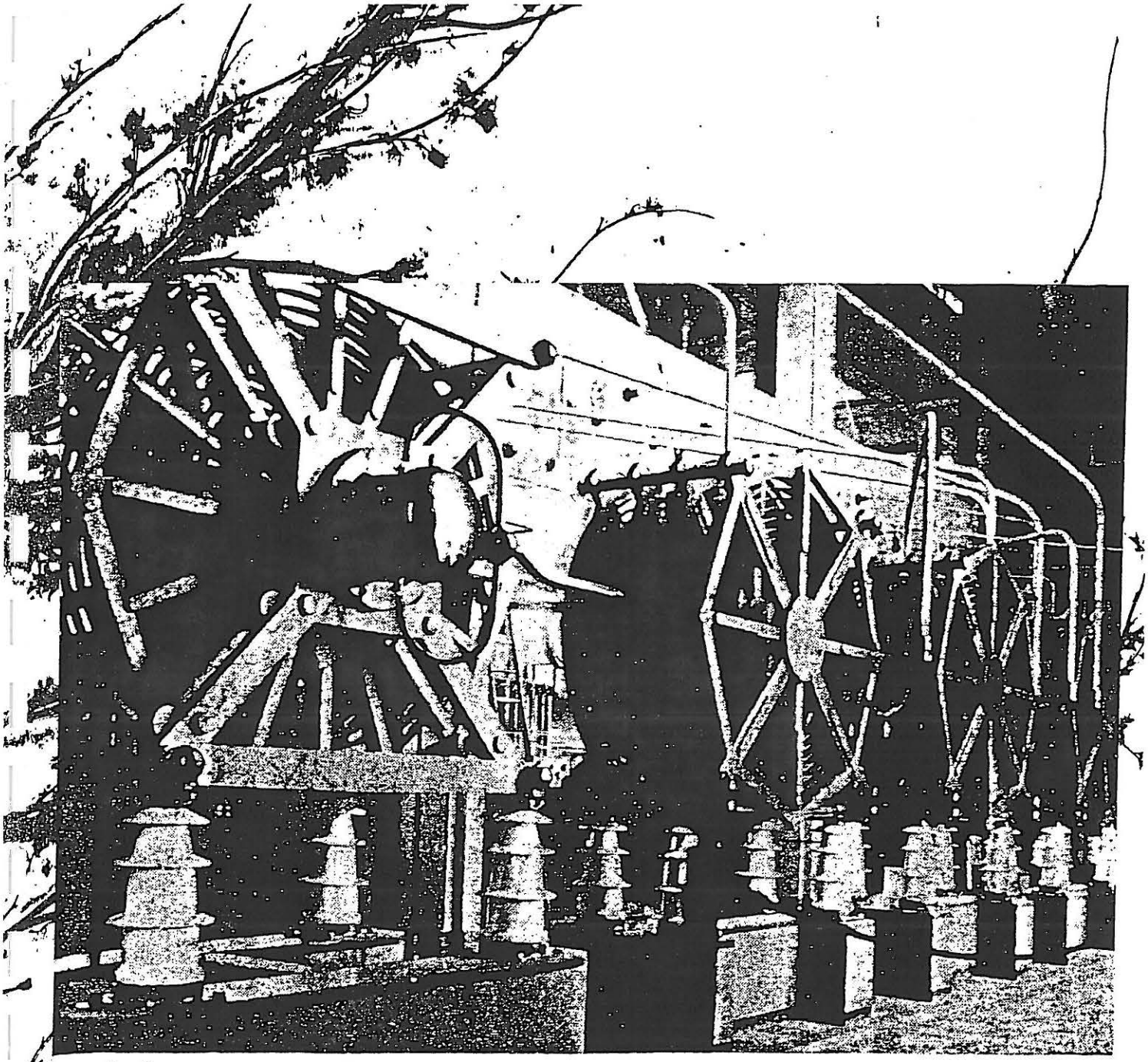


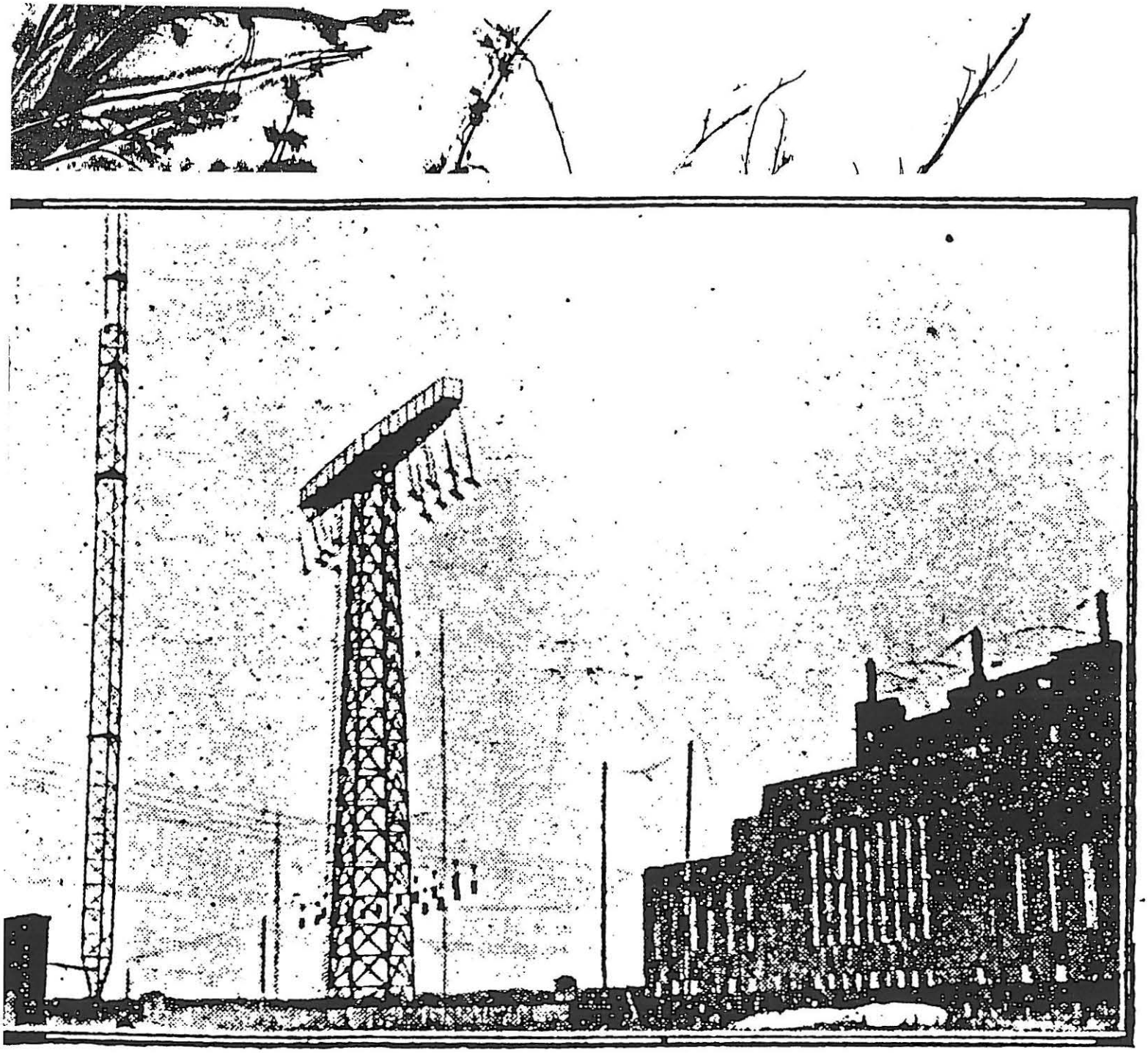
FIG. 135.—Foot of aerial tower showing insulation from ground.



International

GIANT LOADING COILS IN THE RADIO STATION AT NAUEN, GERMANY

The amateur, who deals with electrical powers which are infinitesimal in comparison to those used for trans-oceanic telegraphy, should be careful to use coils that will squeeze out into the antenna even that last little fraction of a watt that is trying to find a small hole to sneak into and peacefully sleep, instead of being shot out into cold space



The huge aerial of the Nauen Station

SANGUINE GROUND AERIAL MATRIX

At long ranges, the radiation pattern of the array, in the Earth-ionosphere waveguide, is bi-directional, just like the horizontal electric dipole and the horizontal line-current antenna. To obtain a steered pattern, or an omnidirectional one, a second array may be superimposed on the first but with its antenna wires lying at right angles to those of the first. Fig. 48 shows a sketch of such an array. This configuration was among those considered by the US Navy for the transmitting antenna of its *Sanguine* communication system [Bernstein *et al.* 1974]. Using many generators emplaced in separate hardened transmitter capsules would make the antenna more resistant to physical attack.

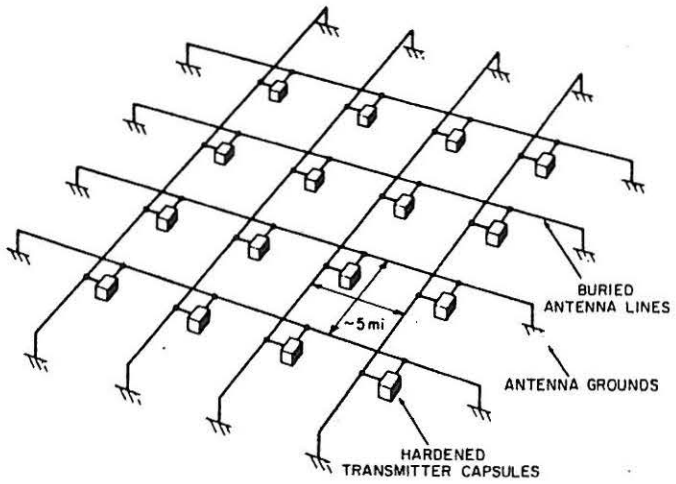


Fig. 48 US Navy's proposed *Sanguine* ELF transmitter array (S. L. Bernstein *et al. Proc. IEEE*, Vol. 62, pp. 292–312, 1974)

The effect that anisotropy of the surface impedance has on the array antenna is not the same as on the single line-current antenna. One significant effect is that although the anisotropy skews the pattern of the antenna, orienting the antenna wires in the same direction as they would lie if the ground were isotropic is close to the optimum orientation. (The optimum orientation is understood here to be that which delivers the required field strength to the receiving area with the least power dissipation. For an isotropic surface impedance and with the receiving area in the far field, the antenna wires are optimally aligned when they lie on great-circle paths passing through the receiving area.) In fact, if the losses in the conductor and in the end grounds are negligible, the optimum orientation is the same as for an isotropic surface impedance. A remarkable feature of the effect of anisotropy is that, although it skews the antenna pattern, even less power efficiency would be obtained if the orientation of the antenna wires were adjusted to swing the peak of the antenna pattern towards the receiving area. Surprisingly, the least power dissipation needed to deliver the required signal strength is obtained by moving the wire orientation in the *other* direction; that is, in the direction which swings the beam peak even further away from the receiving area. A detailed presentation of anisotropy effects is beyond the scope of this work. More details are available elsewhere [Burrows, 1974*c*], but a thorough study of the subject has apparently not yet been made.

4.1.6 Numerical example

The following example of the design of a particular transmitting antenna is included to give some perspective to this discussion. The antenna treated is similar to one of the configurations examined by the US Navy for its *Sanguine* communications system [*IEEE Trans. on Communications*, 1974].

The function of the transmitter is to deliver a horizontal magnetic field of the desired intensity to the receiving area, which might be from 5 to 15 Mm away. The desired intensity is the one which establishes the required communication rate in the presence of atmospheric, and other, noises. Since effective atmospheric noise level for the horizontal magnetic field is of the order of -138 dB re. 1A/m/$\sqrt{\text{Hz}}$, a radiated field strength of -135 dB re.1A/m would result in a 3 dB signal to noise ratio in a 1 Hz bandwidth. This would be sufficient for communication at the rate of 1 bit per second, which would allow, for example, one particular message in a list of 1024 standard messages to be identified in 10 s [Bernstein *et al.*, 1974].

The current moment M required to deliver this signal strength is obtained by combining (2.128) and (2.129) to obtain the following explicit expression for the horizontal magnetic field H_h in the far zone (but not near the antipode) radiated by the horizontal current moment M at range ρ:

$$H_h \sim -\frac{\eta_g M k}{4\eta h_i}\left(\frac{2i}{\pi k a_e \sin\theta}\right)^{1/2} e^{-ik\rho}\cos\phi \qquad (4.112)$$

. In more highly populated regions, the costs of construction would tend to be high as a reflection of the higher price of the land itself and because of the greater density of all the other buildings, pipelines, cables, roads etc. associated with population centers. The presence of population may also make it necessary to perform a certain amount of reworking of the telephone and electric power distribution lines to make them less susceptible to interference from the antenna-wire current. This problem is discussed in the next Section.

In areas remote from population centers, there are concerns of a different kind. The nature of the ground can make the difference between plowing-in a buried antenna cable and burying it by the more costly method of trench and back fill. Access to the area may be difficult and extremes of weather can be troublesome.

Once the search has been narrowed down to one or two specific sites, it is then necessary to measure the electrical surface impedance directly rather than rely on estimates from geological data [Martin, 1972; Bannister, 1976].

The direct method of making the measurement is the magneto-telluric (MT) method which makes use of distant sources, natural or man made, to provide a horizontal magnetic field at the surface. By measuring the strength at the surface of the horizontal magnetic field and the horizontal electric field, and forming their ratio, one may evaluate the surface impedance η as the third member of the relationship, given by (2.30),

$$\boldsymbol{E} = \eta \hat{\boldsymbol{n}} \times \boldsymbol{H}. \tag{4.135}$$

The magnetic field is conveniently measured using a receiving loop antenna with its axis horizontal. A horizontal insulated-dipole receiving antenna, with its ends grounded in the Earth, is the antenna to use to measure the horizontal electric field. The arrangement is sketched in Fig. 53, showing two crossed loops and two crossed dipoles to allow the anisotropy of the impedance to be measured also. The length of each dipole could be longer than the sketch suggests, to increase the voltage induced in it. Other magnetic field sensors may be used, too. Instead of the air-core loop sketched, a loop with a ferromagnetic core might be used or even a magnetometer. The dipoles and loops are essentially receiving antennas. They are described in the next Chapter.

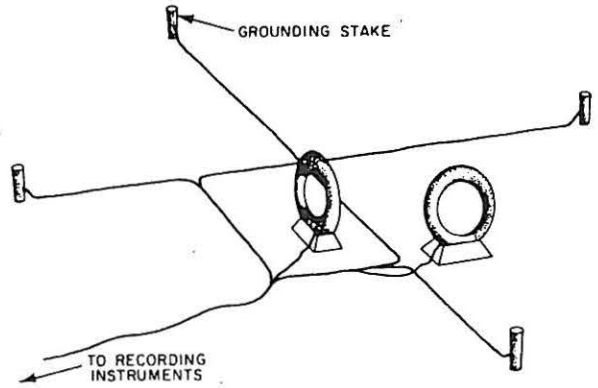
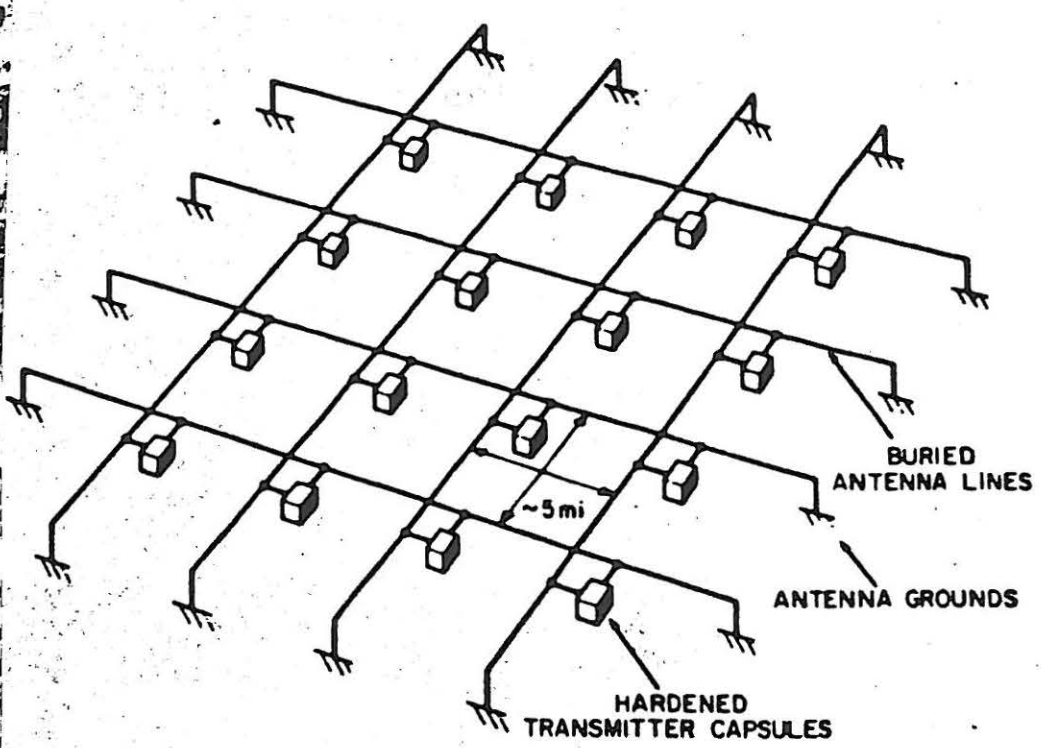


Fig. 53 Arrangement of receiving antennas to measure surface impedance by the magneto-telluric method

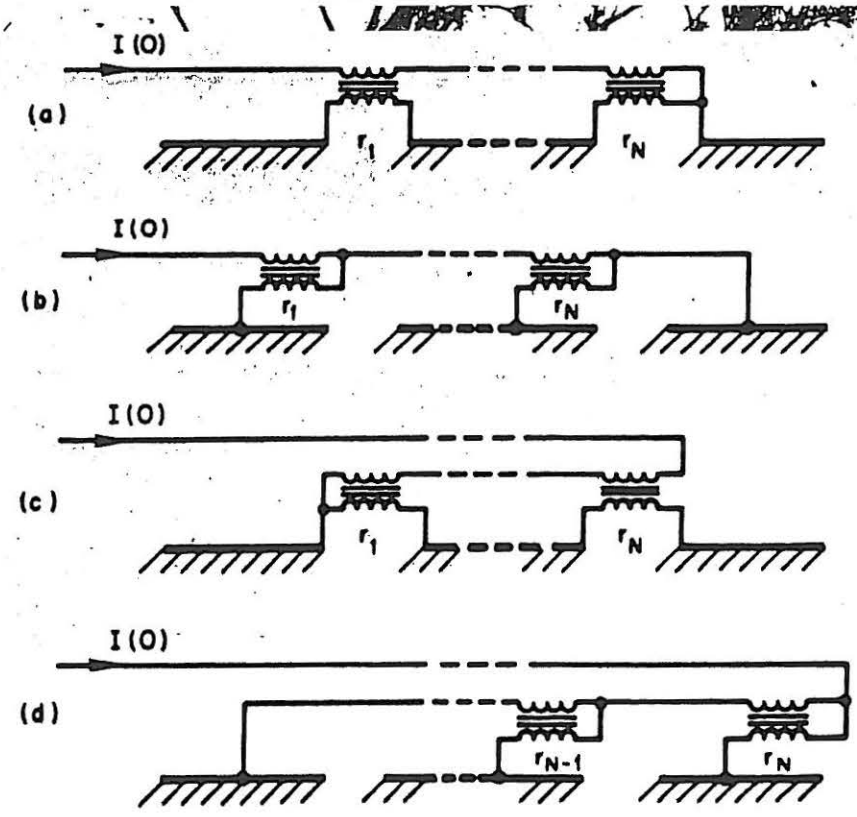
The magneto-telluric measurement of the surface impedance should be performed at the operating frequency planned for the transmitter. It also should be performed at a sufficient number of locations, over the area to be used by the transmitting antenna, to be sure that the results fully characterize the area.

In this regard, it should be noted that the magneto-telluric method is used in geology to deduce the resistivity of the ground as a function of depth. The resulting curve can then be used to infer the geology down to considerable depths. To do this, however, the measurement must be repeated at a number of different frequencies at the same location. The lowest frequency used determines the maximum depth to which the method is sensitive to the resistivity. Thus, if in surveying a potential ELF transmitting antenna site, the magneto-telluric measurement is made at other frequencies besides the planned operating frequency, a more thorough geological understanding of the area can also be obtained. If the magnetio-telluric measurements are consistent with the original assumed geology of the site, or if they lead to its revision, a better understanding of the site will have been obtained.

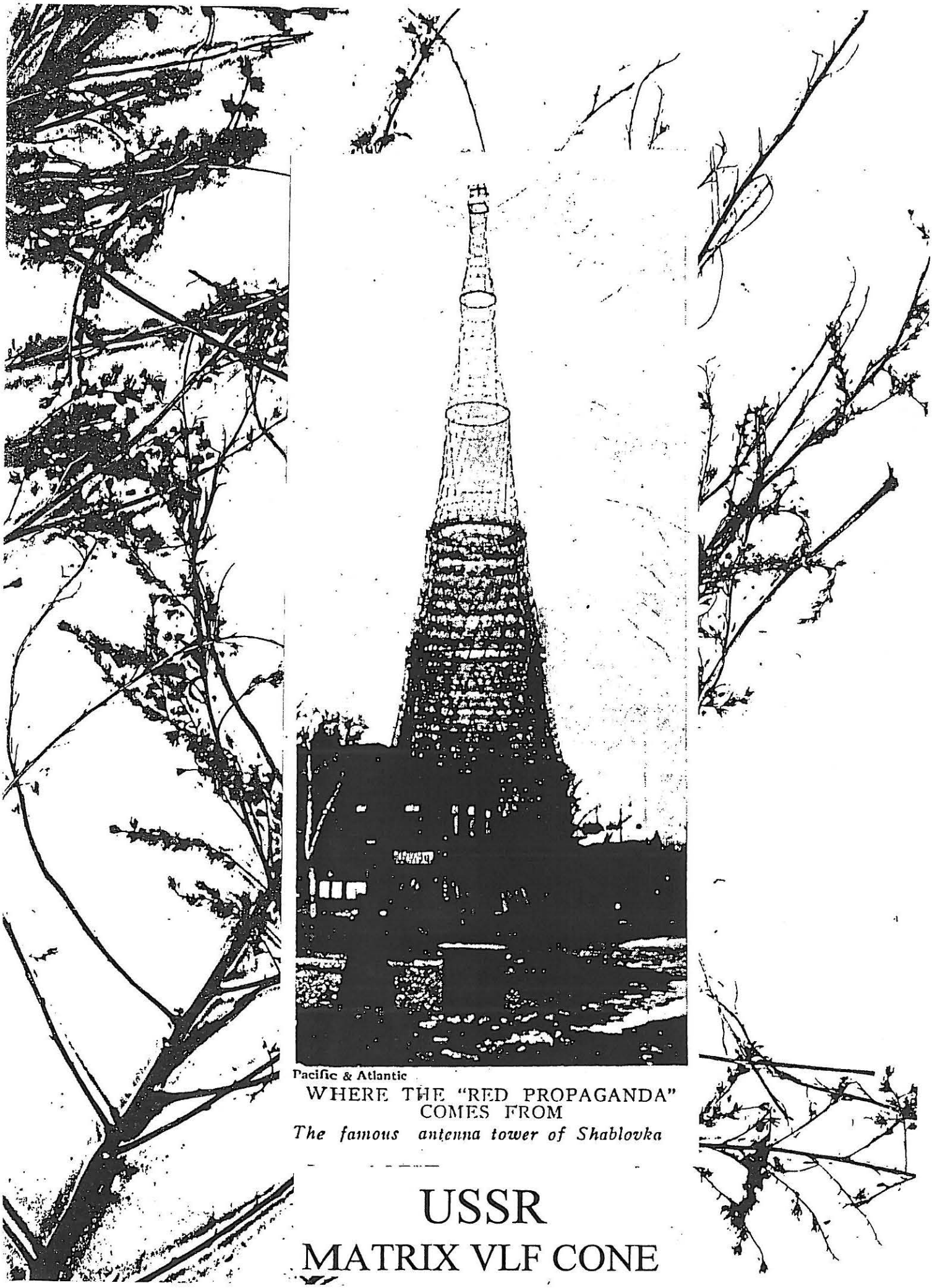
Fig. 48 shows a sketch of such an array. This configuration was among those considered by the US Navy for the transmitting antenna of its *Sanguine* communication system [Bernstein *et al.* 1974]. Using many generators emplaced in separate hardened transmitter capsules would make the antenna more resistant to physical attack.



US Navy's proposed *Sanguine* ELF transmitter array (S. L. Bernstein *et al. Proc. IEEE,* Vol. 62, pp. 292–312, 1974)



Four types of transformer connection showing the insulated connecting cables and bare grounding conductors.



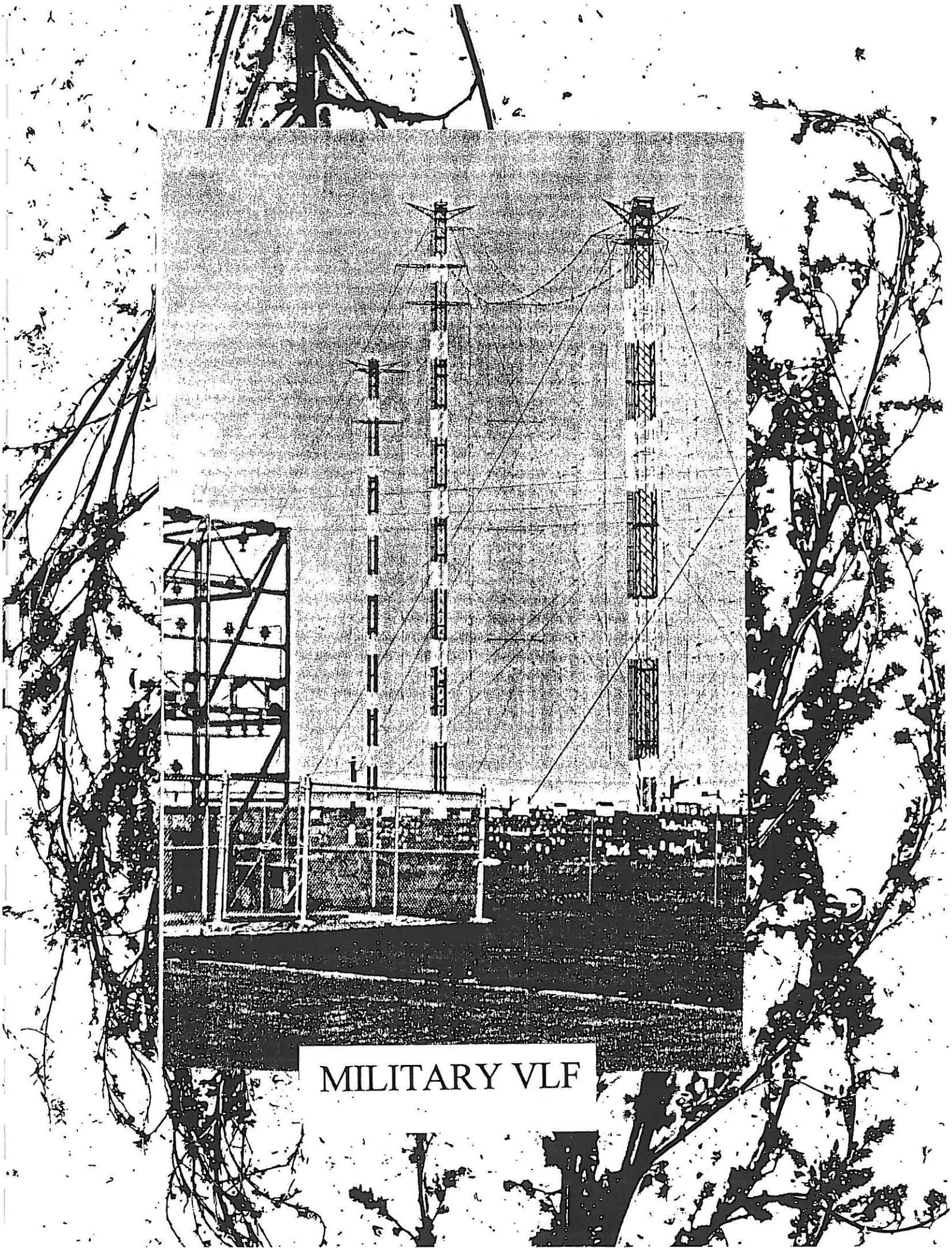
Pacific & Atlantic

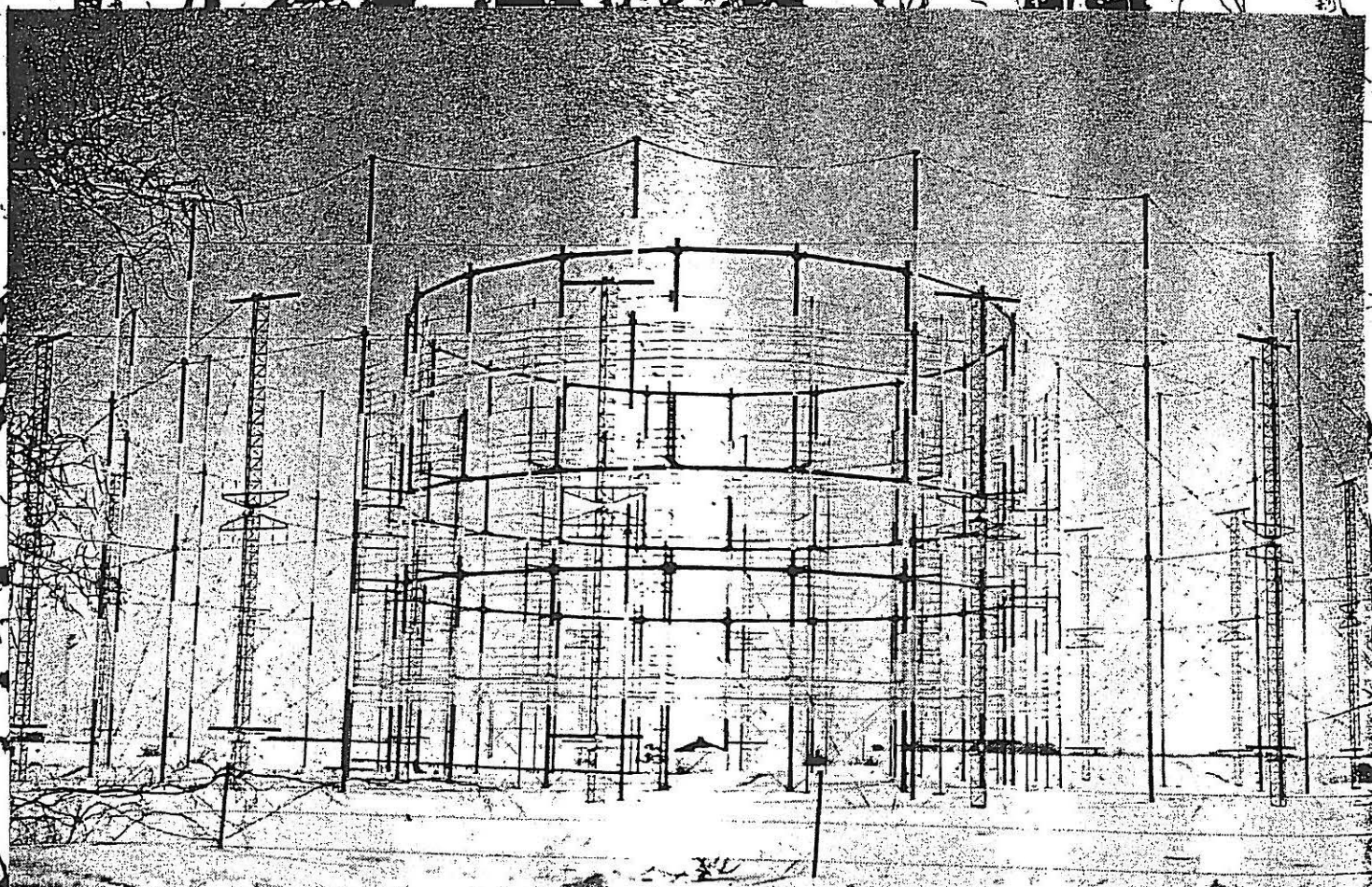
WHERE THE "RED PROPAGANDA" COMES FROM

The famous antenna tower of Shablovka

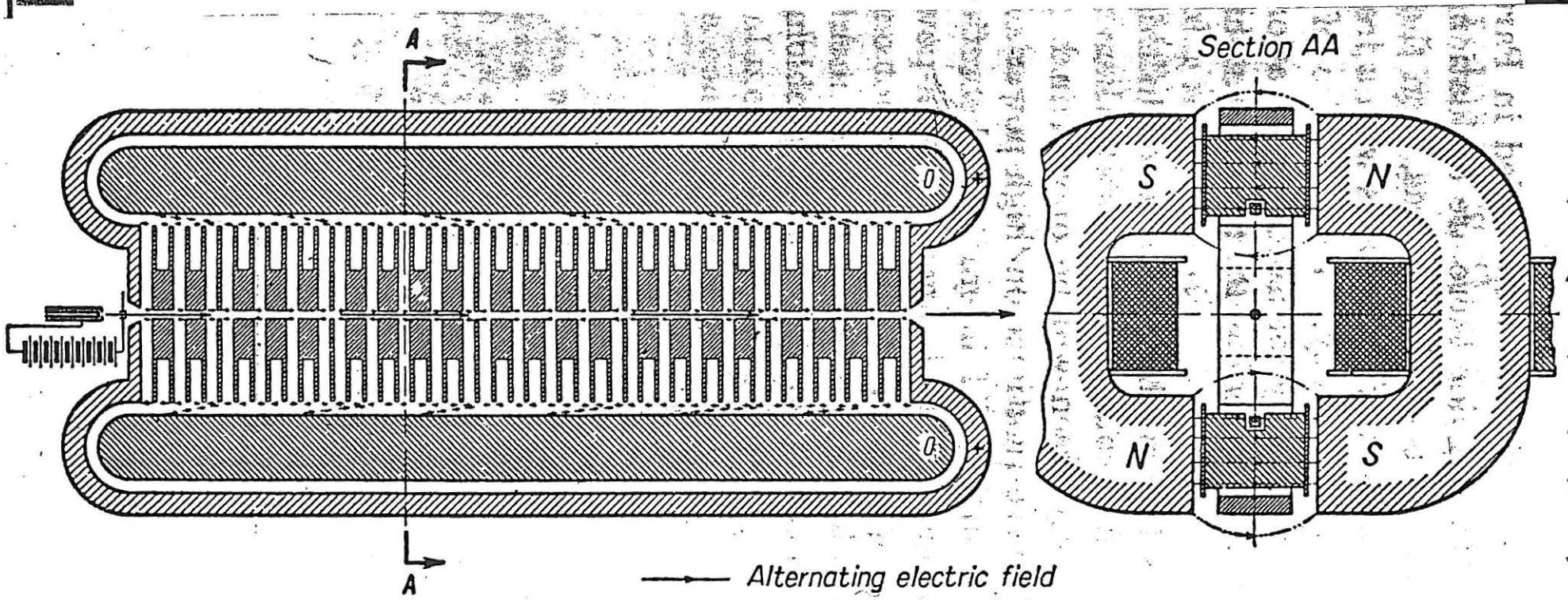
USSR

MATRIX VLF CONE


MILITARY VLF



MILITARY
ELF
COIL TRANSMITTER



USSR
PLANATRON
GIGAWATT RADAR BEAMS
DR. P. L. KAPITZA

SECTION 4

MILITARY ELF



Radio Uses

NO ETHER WAVES

By WALTER W. MASSIE

The author, whose portrait appears at the left, is one of America's earliest and best known radio pioneers. He has never accepted the conventional ether-wave theory of radio. In this article he explains an alternative theory—a theory which assumes that radio is propagated along the magnetic field of the earth.

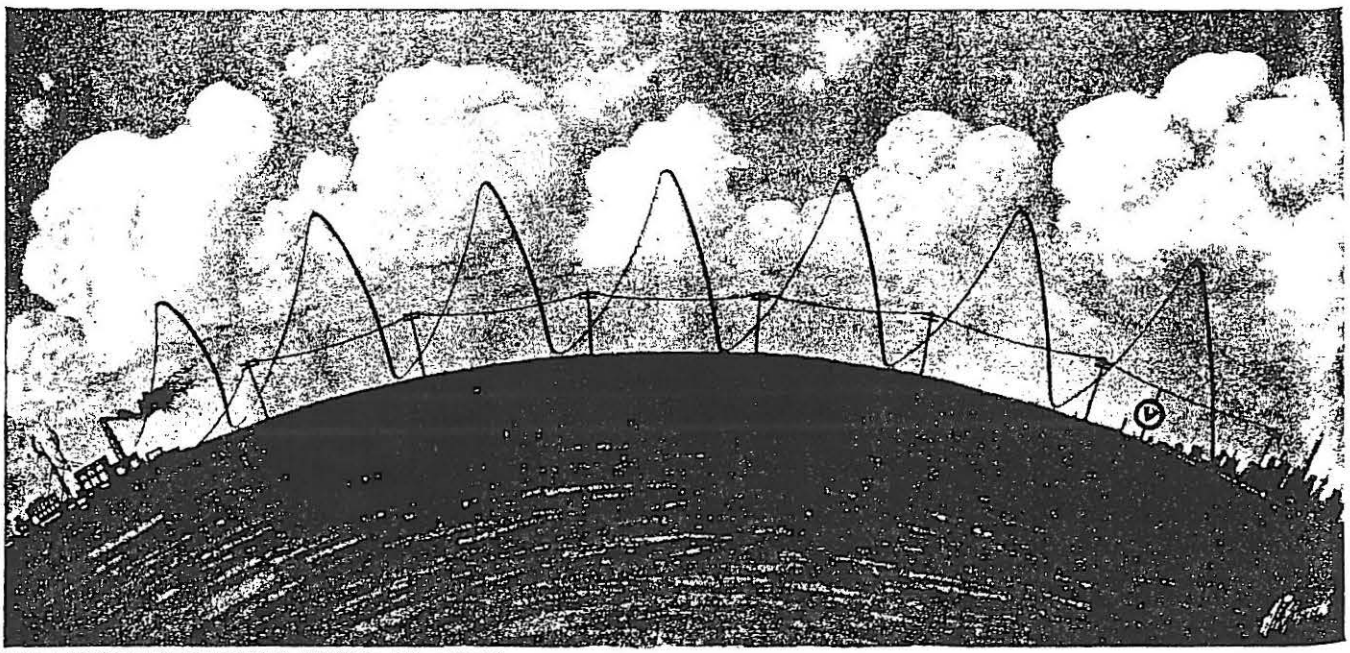
SCIENTIFIC theories and traditions are a good deal like religious creeds. It is heresy for the ordinary scientist to depart from them.

This fact was strongly impressed upon me twenty-five years ago when I could not accept the prevalent theory that wireless was propagated by free Hertzian waves. During my work of more than a quarter of a century on the subject of wireless I have found it best to stay down upon the earth and have been able to explain all radio phenomena with the magnetic wave theory.

When the theory was advanced that wireless was propagated by free Hertzian waves, traveling in straight lines like light I could not accept that theory. The early results obtained did not seem to support it and as far as I was concerned it took a lot of explaining to show how signals could travel around the globe.

In my home I set up a small transmitter automatically operated by a clock to give signals at short intervals. Carrying a microphonic receiver around the house to test the signal strength at different distances from the transmitter, I found that the signal strength was strongest near a lighting fixture, regardless of the distance from the transmitter. There was no doubt the wireless waves were following the conductors provided by the lighting installation.

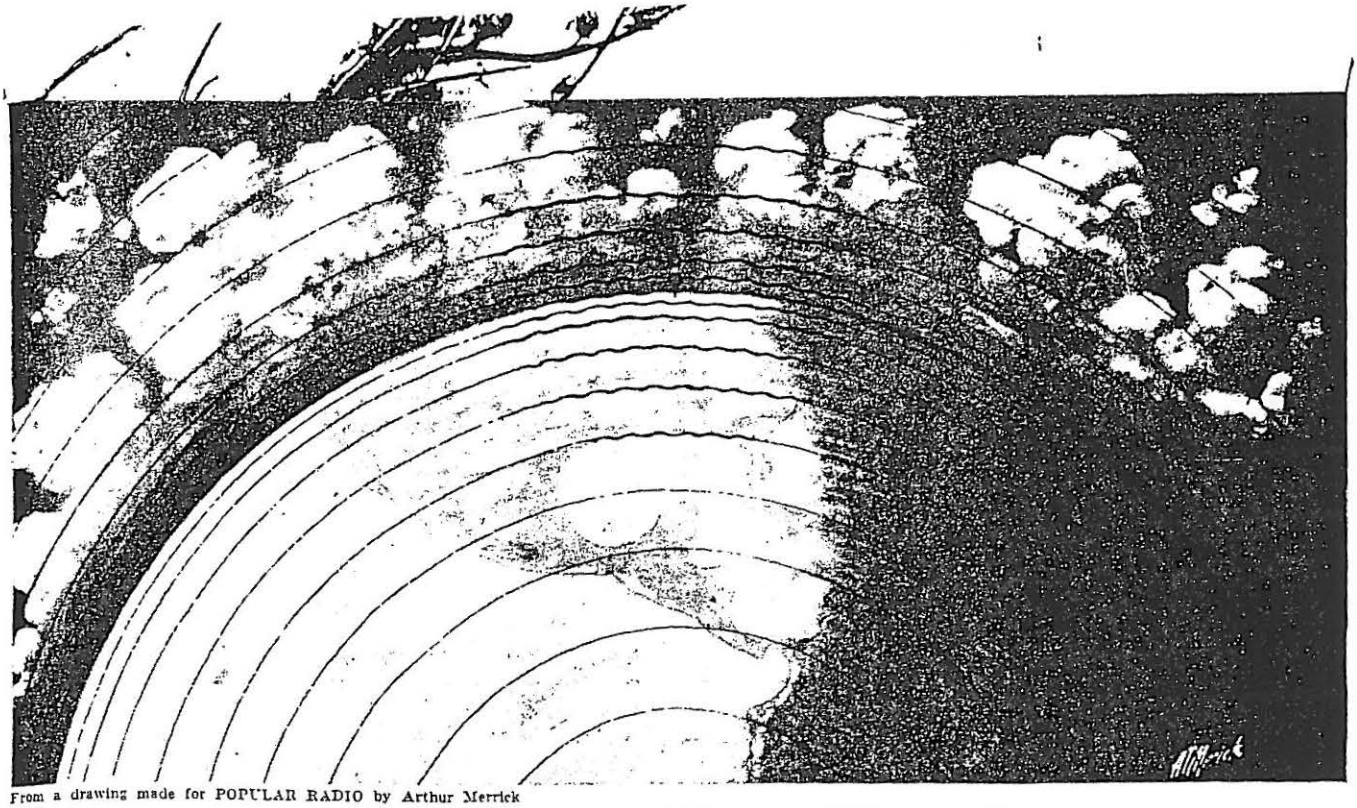
With a "filings" coherer and a bell for a receiver and a buzzer for a transmitter I began experimenting and found that the buzzer would ring the bell a foot away from the coherer. But if a wire of any length was stretched out with one end near the coherer, the buzzer would ring the bell when operated at any point



From a drawing made for POPULAR RADIO by Arthur Merrick

HOW THE MASSIE THEORY COULD BE TESTED

The telegraph line, grounded at both ends, is set up between the transmitting station and the receiving one. A voltmeter inserted in this line registers the potential of the earth currents. This potential will correspond, Mr. Massie believes, with the perfection of radio transmission between the two stations.



From a drawing made for POPULAR RADIO by Arthur Merrick

RADIO IS CARRIED BY THE EARTH'S MAGNETIC FIELD

According to the Massie theory the lines of force of the magnetic field run parallel to the earth's surface. They are disturbed by a radio transmitter, as is indicated in this drawing, by the crinkles in the magnetic lines. These disturbances are propagated along the lines of magnetic force, thus producing the radio phenomena.

along this artificial ground. There was no doubt that the wireless waves followed the conductor. I then formed my grounded magnetic wave theory and in the book* of which I was co-author, I set forth my theory as follows:

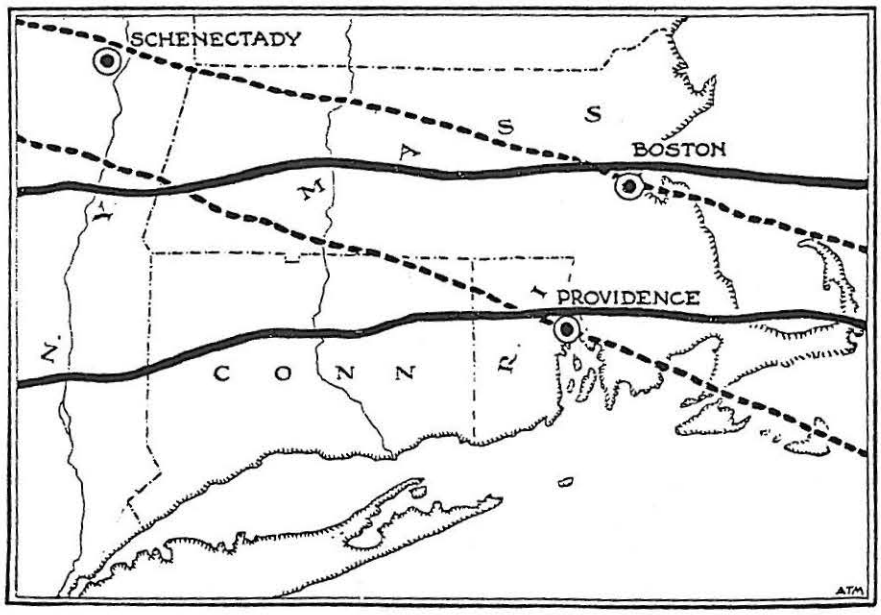
> "Wireless signals are a wave motion in, or disturbance of, the magnetic forces of the earth, and are propagated through this magnetic field, following the curvature of the earth, just as a tidal wave would follow the surface of the ocean. Practice indicates that the nodal points of the waves are at, or near, the earth's surface."

This theory which I began testing as far back as 1902 and which the work of other investors indicated was the correct theory, I thought had been universally accepted. But the theories now being advanced to explain fading indicate radio scientists are getting back into the air again. Fading can be explained by my theory of grounded magnetic waves and can be definitely settled by certain corporations or by the Federal government which has experimental use of telephone or telegraph lines.

We know there are earth currents, that they vary in strength and that they travel in paths of least resistance. Charts have been made to show the earth current paths.

Every telegraph operator has to contend with these earth currents. If one end of a long telegraph or telephone line is grounded and the other end tested for voltage it is found at times the potential impressed by the earth currents alone may run into hundreds of volts. As a matter of fact in the operation of long distance telegraph lines it is necessary to watch the earth currents with a great deal of care and adjust accordingly the current fed into the line from the batteries.

One day in the fall of 1903 when I was installing a wireless station at Point Judith, R. I., the telegraph companies reported the earth currents exceptionally strong. At the same time it was noticed that the wireless reception was



HOW EARTH CURRENTS AFFECT RADIO

When the paths of the earth currents follow the heavy lines western stations will be received well at Boston and Providence. If the direction of the earth currents shifts to that of the dotted lines, Schenectady will be exceptionally strong at Boston. Radio moves best along the lines then being followed by the earth currents.

* "Wireless Telegraphy and Telephony," published 1908.

extraordinarily good, indicating there is a direct connection between earth currents and radio reception.

The stronger the earth currents, the stronger the resultant magnetic field and the greater the distance the radio waves will travel and the greater the strength of signals at the receiver. Earth currents are constantly varying in strength and follow paths according to the conductivity of the earth's strata. When we have compiled enough data on these earth currents, I believe we will have an explanation of practically every radio problem not yet satisfactorily solved.

Of one thing I am certain; it has been demonstrated to my satisfaction, time and again during the past twenty-six years, that there is a very definite relation between the signal strength and transmission distance and the strength of the earth currents. I feel certain that radio waves travel greater distances when following along the earth-current paths. This by itself explains some of the peculiarities of radio reception.

On land, due to the almost constant change that is taking place in the conductivity of the earth-current paths, more current may be traveling at a given time in one path and at another time in another path. These currents vary not only from day to day but also from path to path. There is nothing about them that seems fixed.

Now let us suppose that on one night the earth currents in the most direct path between the broadcasting station and the receiving station are exceptionally strong, that this path has less resistance than any other path between the two stations. We would then expect to have great signal strength and exceptionally good reception. There is reason to believe this is actually the case.

Suppose, however, that on the following night something has happened to make the strength of the current in this path almost equal to that flowing between the stations by more circuitous paths. The waves that come together after traveling over different paths might not be exactly in place. As a matter of fact those in one path might be lagging behind or leading the others by just the right amount as to counteract each other and there would be no signal at all at the receiver. If the waves from the two paths were slightly out of phase, they would periodically re-enforce and then counteract each other and the signal strength would build up and then fade away.

Under these conditions, fading would ordinarily be most pronounced on the most distant stations and less pronounced on those stations nearest the receiver. However, on account of the peculiarities of earth currents and their paths and the great number of things that may affect these currents and their paths this could not be adopted as a universal rule.

I am not trying to advance a proved theory; I am merely submitting an idea that I believe is worth careful thought and extensive investigation. It is obvious that the simple experiments I conducted to satisfy myself that radio waves are really grounded magnetic waves would not suffice to demonstrate that fading is caused by earth currents. Much more study must be given to earth currents than has ever been given before. A vast amount of data we do not now possess must be compiled.

It will require extensive research over a wide area to establish this idea as a theory. I believe, however, that work along this line is along the right line, and that it is possible to establish positive proof of my claims.

Therefore, I pass along the idea with the hope that it will be taken seriously by enough investigators to enable us, during the next few years, to gain the knowledge of earth currents and their relation to radio that is necessary to establish it as a proved theory—a theory that will show in a sound and satisfactory manner the cause of fading.

MASSIE

TRANSMITTING ALONG MAGNETIC MERIDIANS

The Secret of Wireless Telegraphy

The rate of vibration in the ether, as artificially produced in wireless telegraphy, is extremely slow as compared with that of the light waves, ranging from approximately 1,500,000 to 100,000 per second. The wave length, in any such case, is found by dividing the velocity by the rate of vibration; hence for the extreme violet of the spectrum, the wave length would be $\frac{1}{64000}$ inch, and for the extreme red, $\frac{1}{33000}$ inch, while those employed in wireless telegraphy vary from about 650 feet to nearly two miles.

As is well known, the ether in proximity to the earth is in continual disturbance, which creates the magnetic field surrounding the earth. This manifests its presence in many ways; the most common is its influence on the magnetized needle of a compass, which causes it to point north and south. Wireless waves are propagated through this magnetic field, and follow the curvature of the earth.

When we contemplate the wonders of nature, and gradually fathom her mysteries, that which before seemed impossible now becomes an established fact.

Referring to Fig. 3, let C represent a capacity connected to the ground MN through the adjustable inductance I. If means be employed to cause the residual charge of this capacity to oscillate, it will, in turn, cause a wave-like motion of the electromagnetic forces of the earth similar to the wave motion in water.

If either the capacity or inductance is increased, the vibrations will be slower, and the wave length will be

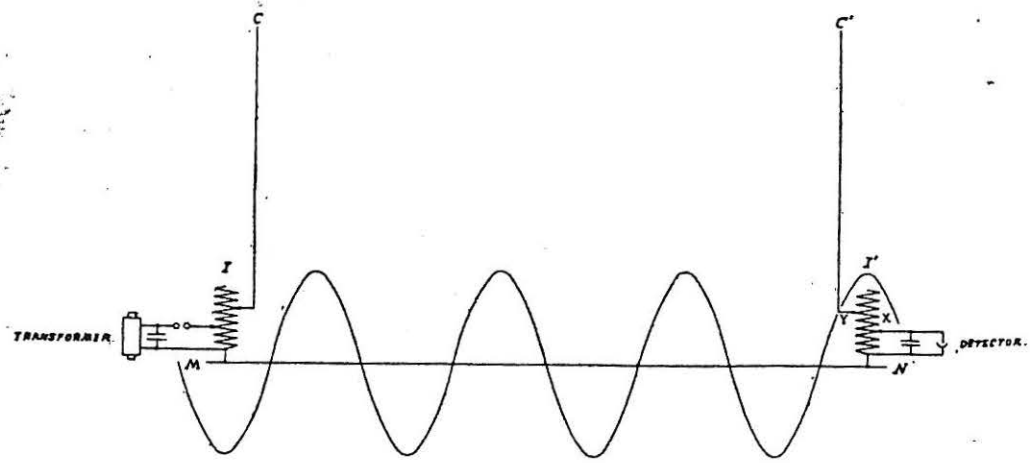


FIG. 3.—THEORY OF WIRELESS TELEGRAPHY.

greater. The waves thus generated are propagated through the earth's forces in ever-increasing circles, exactly as in the case of the water waves.

C' in Fig. 3 represents the receiving capacity connected to the ground through the inductance I', in the same manner as at the sending station. This capacity, of course, also contains a residual charge which is dormant under normal conditions, but as the wave front glides by the station, the rising and falling of the waves will impart a slight oscillatory motion to the residual charge.

MAGNETIC LINES AND RADIO COMMUNICATIONS

Wireless signals are a wave motion in, or disturbance of, the magnetic forces of the earth, and are propagated through this magnetic field, following the curvature of the earth, just as a tidal wave would follow the surface of the ocean. Practice indicates that the nodel points of the waves are at, or near, the earth's surface.

As explained in Chapter I, ether waves do not traverse all substances with like velocities; this explains why wireless signals are propagated many times farther over water than over land, as the waves traverse air and water at practically the same velocities. In land the waves travel at a much slower rate.

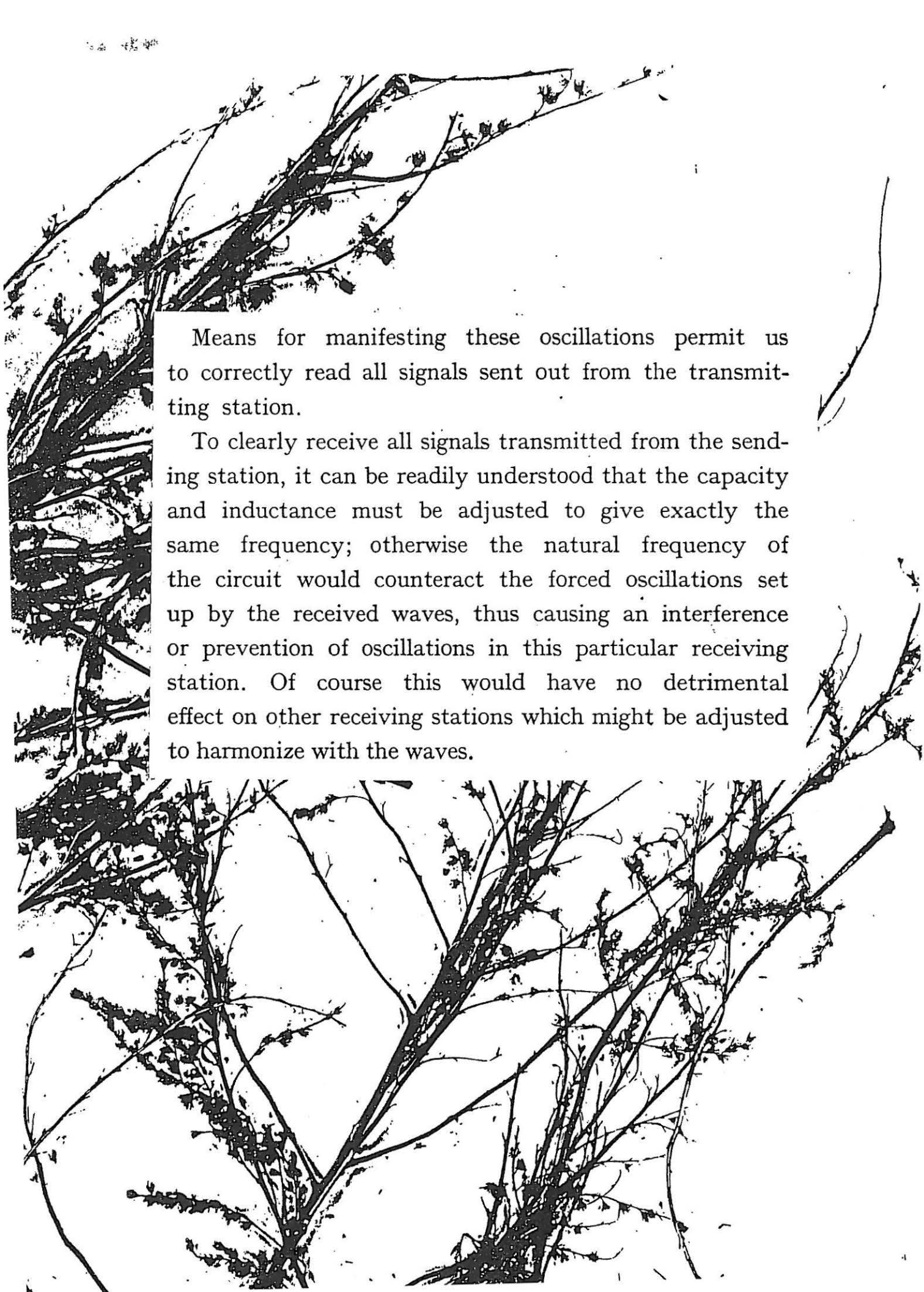
Now to produce, electrically, the results described by the analogy of water, we must employ means for creating waves in the earth's magnetic field, and use an electrical spring and weight, so to speak. The electrical spring effect is obtained by the electrical phenomena of *capacity*. Any surface of metal possesses capacity, which is the power to retain a charge of electricity. When this is disturbed it has the same elastic principle as the spring.

The inertia of the weight is represented, electrically, by the term *inductance*, which effect is produced when a constantly changing current is passed through a coil of wire. This causes the continually changing current to react upon itself, and, consequently, produces a retarding effect.

it oscillates uniformly, it will create, or generate, a definite number of waves per minute, all being of uniform length and size.

If now we substitute a similar spring and weight for the chip as a receiving device (shown at the right in Fig. 2), and place this within the radius of the transmitted waves, these waves in passing will set it in motion, as it oscillates at exactly the same frequency as the transmitting weight. If the receiving device did not oscillate at the same rate as the transmitter, and, therefore, was not in harmony with the transmitted waves, these would tend to counteract any motion imparted to the receiving spring-suspended weight, as the following example should make clear. Assume the receiving weight to be of such dimensions that it will oscillate once per second. Now if the sending weight be generating waves at the rate of two per second, the first wave will give the receiving weight an upward motion at its own frequency; but just as it starts on its downward stroke, the second wave will strike it, thus preventing any further motion of the weight.

It is, therefore, evident that the escillations of the receiving device would be destroyed if the frequency did not harmonize with that of the sending device. Tuning is absolutely necessary for the successful operation of wireless telegraphy, and it should be thoroughly understood before continuing.



Means for manifesting these oscillations permit us to correctly read all signals sent out from the transmitting station.

To clearly receive all signals transmitted from the sending station, it can be readily understood that the capacity and inductance must be adjusted to give exactly the same frequency; otherwise the natural frequency of the circuit would counteract the forced oscillations set up by the received waves, thus causing an interference or prevention of oscillations in this particular receiving station. Of course this would have no detrimental effect on other receiving stations which might be adjusted to harmonize with the waves.

PROPAGATION OF AUDIO-FREQUENCY RADIO WAVES TO GREAT DISTANCES

By Dr. F. W. CHAPMAN and R. C. V. MACARIO
Wheatstone Laboratory, King's College, London

THE propagation of low-frequency radio-waves was studied many years ago using long-wave commercial transmitters. The well-known Austin–Cohen law was widely used for estimating field-strengths, and because of the theoretical justification of its general form this law was used as a basis for the computation of attenuation coefficients at very low frequencies. According to the law, the attenuation of signals decreases as the frequencies decrease ; in fact, at a frequency of 3 kc./s. or less, the attenuation would appear to be very small indeed. The absence of observations at frequencies less than about 12 kc./s., however, meant that the mode of propagation of radio waves at lower frequencies was for many years the subject of speculation.

Now in the course of our observations on the electromagnetic waves radiated by lightning discharges, we have found evidence of a high attenuation of waves in the frequency-range of 2–3 kc./s., in complete contradiction to that predicted by the Austin–Cohen law.

In the original observations on these naturally-occurring disturbances known as atmospherics[1], it was found that they acquired characteristic patterns during their passage between the ground and the ionosphere. An inspection of their wave-forms up to very considerable distances from the source clearly showed that the main concentration of energy lay in the audio-frequency band below 10 kc./s. and that the higher-frequency components moved forward relative to the lower-frequency or 'slow tail' components as the distance of propagation increased. Furthermore, it was observed that a band of frequencies in the neighbourhood of 2 kc./s. was either entirely missing or at least very heavily attenuated. This band of missing frequencies lay between the predominant frequency of the characteristic 'oscillatory head' and the 'slow tail' of the atmospheric and, as was stated earlier[1], unless there is some factor operative corresponding to anomalous dispersion for the missing frequencies, the higher-frequency group and the slower disturbance do not originate in exactly the same portion of the discharge.

It is pertinent to remark here that Eckersley in his early studies of radio-transmission[2] questioned the continued validity of the Austin–Cohen law with decreasing frequency of the wave. In fact, he suggested a theoretical reason for supposing that the attenuation ceases to decrease at frequencies lower than about 12 kc./s.

In order to elucidate this problem, we have, during the past few years, supplemented atmospheric wave-form observations by simultaneously recording the relative amplitude of the frequency components in the spectrum of the wave-form. In their first experiments, Chapman and Edwards[3] recorded the wave-forms and corresponding response of a number of narrow-band receivers tuned to frequencies in the range 1–25 kc./s. The amplitude of the various frequency components was calculated from these responses and the observed spectrum of atmospherics due to lightning strokes between the cloud and ground compared with that to be expected from this type of discharge. Later, Chapman and Matthews[4] used an improved apparatus covering the frequency range 40 c./s. to 16 kc./s. split by twenty-seven band-pass filters arranged logarithmically at three channels per octave. Here the amplitude-frequency spectrum was presented directly on the screen of a cathode-ray tube and photographed along with the corresponding wave-form. They discussed the relation between the well-known wave-form characteristics and the significant changes in the spectrum as the distance of propagation increases.

In our more recent experiments we have applied magnetic tape sound-recording techniques[5] to obtain permanent records of the complete history in time of all the disturbances appearing at the aerial (a vertical rod). A second channel on the tape, linked by telephone line to the Meteorological Office C.R.D.F. network for locating thunderstorm centres, provides information on the source of individual

atmospheric disturbances. The random distribution of the different types of atmospheric and their amplitude in relation to the continuous background noise-level at the site can thus be readily assessed. The spectrometer has also been modified to record single waveforms and their amplitude-frequency-spectra at a maximum rate of one record per second, and an electronic switching device ensures that spurious signals do not add to the spectrum recorded.

The results to be described are based on one particular type of atmospheric, namely, that resulting from cloud-to-ground discharges and at known distances up to about 4,000 km. Observations have been made under both day and night conditions of propagation and at different seasons of the year. The attenuation coefficient of signals in the frequency range 40 c./s. to 16 kc./s. has been computed from the experimental results for both land and sea paths and different ionospheric conditions. In all cases the presence of a marked absorption band has been found at a frequency of 1 or 2 kc./s. Finally, the results obtained are compared with the earlier long-wave transmission results and the more recent theories of propagation.

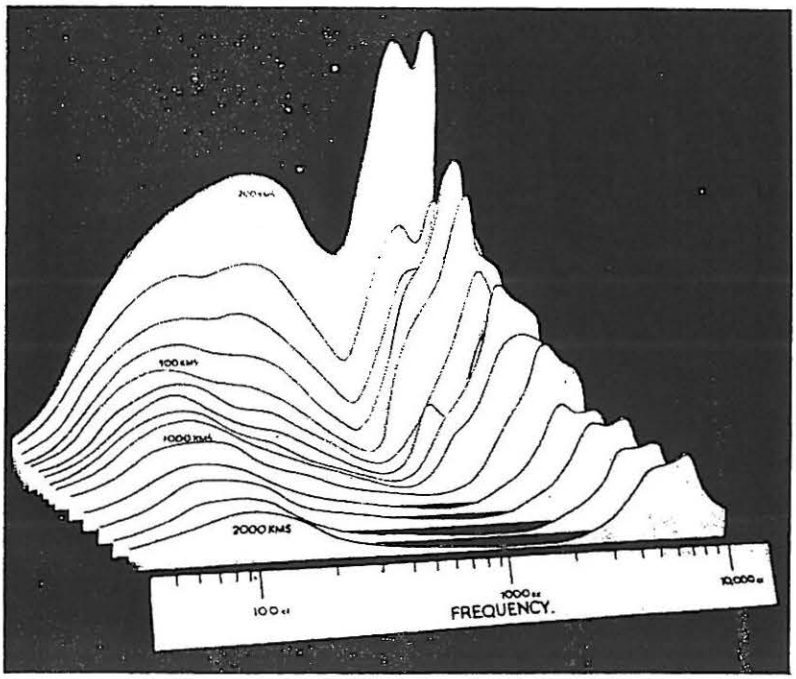


Fig. 1. Model showing the relative amplitude of the frequency components of atmospherics resulting from an average cloud-to-ground lightning stroke observed by day at different distances from the source. The vertical scale shows relative amplitudes in micro-volt, sec./metre (1 cm. in the model corresponds to 10 micro-volt, sec./metre)

In Fig. 1 is shown a photograph of a model illustrating the way the spectrum of the disturbance radiated by an average cloud-to-ground lightning stroke varies with the distance of propagation. This particular model was constructed from a large number of observations made on land sources at noon during winter months. It clearly shows that with increasing distance the various frequency components, besides falling off in amplitude due to a two-dimensional divergence of energy, also suffer selective attenuation due to ionospheric influences as had previously been reported by Appleton and Chapman[1]. The preponderance of energy in the highest and lowest frequency-ranges represents the familiar 'oscillatory head' and 'slow tail' parts of the wave-form, respectively.

It is not our purpose to discuss here the various types of disturbance and their characteristic spectra; but it should be mentioned that frequently the 'slow-tail' components are either absent or at least very small. This is undoubtedly an effect of the source dependent on the mode of destruction of the thunder-cloud charge by the lightning stroke, that is, whether or not the current in the discharge channel rapidly decreases after the 'return stroke' has reached the cloud[6]. However, in all cases of both high- and very low-frequency radiation at the source, there is an absorption band in the spectrum of the distant atmospheric which is clearly the result of propagation. This phenomenon, together with the law of propagation at these very low frequencies, are the subject of our present discussion.

In dealing with our experimental results, we are faced with two problems. What is the strength of the signal radiated at the source on any particular frequency channel, and how does propagation affect the amplitude of the signal observed on this channel at a distance ? It will be seen that we cannot interpret our observations without some knowledge of one or the other.

The diverse nature of lightning discharges makes it difficult to derive any useful data on the spectrum of the radiation field at the source, although some information already exists for a simple type of discharge[3,7]. However, as regards the effect of propagation, it is possible to be more definite.

It is well known that electric waves of very low frequency are guided around the earth by the ionosphere and, as already indicated, many attempts have been made, both empirical and theoretical, to derive expressions for the signal-strength $E(f,r)$, where f is the frequency and r the distance of propagation. A survey of the extensive literature on the subject indicates that the main contribution to the signal-strength may be represented by an expression of the form

$$E(f,r) = A(f)r^{-1/2} \exp\,[\,-\alpha(f)r]$$

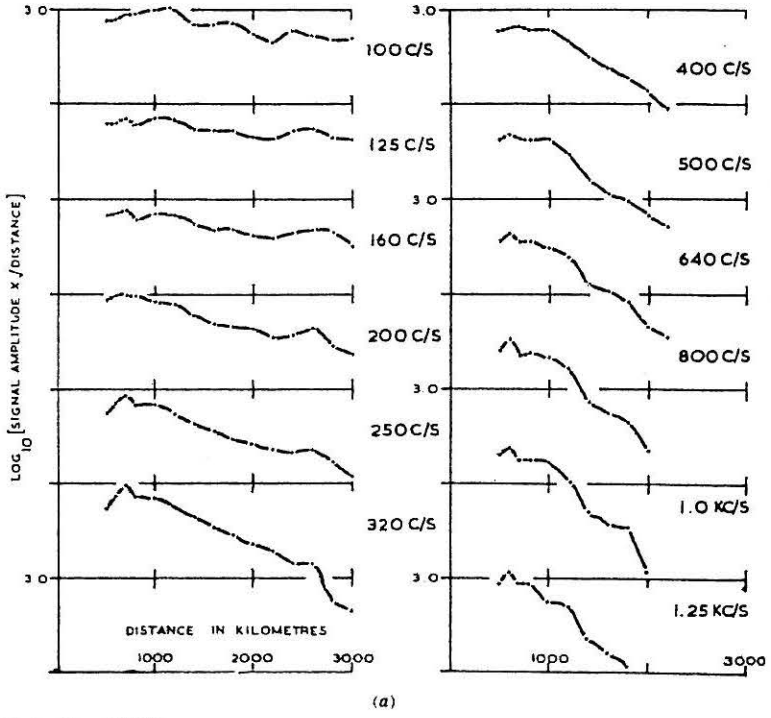
(200 km. $\leq r \leq$ 3,000 km.), where $A(f)$, the amplitude coefficient, depends on the spectrum at the source and $\alpha(f)$ is the attenuation coefficient.

This is essentially the formula used by Round, Eckersley, Tremellen and Lunnon[8] for the interpretation of their observations on the propagation of signals from long-wave transmitters (frequencies down to 12·5 kc./s.), and as will be seen later, there are good grounds for assuming that the formula may be applied at much lower frequencies.

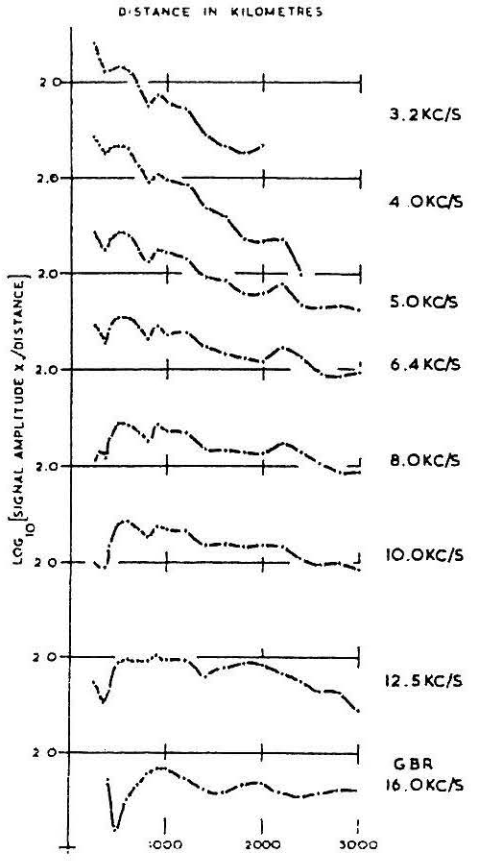
According to the above expression, the value of the quantity $\log\,[E(f,r)r^{1/2}]$ at any particular frequency varies linearly with the distance r, so that the value of the attenuation coefficient $\alpha(f)$ at that frequency can be determined directly from the slope of the line obtained by plotting the results in this

way. This was the method used by Round and Eckersley[8] and later by Budden[9] in his discussion of the measurements made by Weekes on the field-strength of the 16 kc./s. Rugby transmitter *GBR*.

In Fig. 2 (*a*) and (*b*) we have plotted our results for a number of frequency components derived from the spectrum of atmospherics and ranging from a frequency of 100 c./s. to 12·5 kc./s. For comparison, the corresponding curve given by Budden[9] for *GBR* is included. It will be seen that each curve shows a characteristic variation with distance more pronounced at shorter distances. Budden considered that the variations in field-strength for *GBR* could be explained in terms of the interaction of two predominant modes of propagation in the wave-guide bounded by the ground and the ionosphere. Ya L. Al'Pert[10] also calculated this kind of variation of signal-strength with distance for *GBR*. The striking similarity in the form of the curves derived at lower frequencies using atmospherics and that measured by Weekes and Budden for *GBR* transmissions is to be noted. Also, the results for frequencies less than 1·5 kc./s. do not show this effect so markedly.



(*a*)



(*b*)

Fig. 2 (*a*) and (*b*). Variation with distance of log $E\sqrt{(r)}$ at different frequencies. (The interval between horizontal lines represents one unit on the logarithmic scale)

Evidently, by smoothing out the effect of the secondary modes of propagation, the mean slope of the straight line obtained for each channel gives a value for the attenuation coefficient of the principal mode or main signal contribution on that channel. The values of $\alpha(f)$, expressed in decibels per 1,000 km. path, are plotted against frequency in Fig. 3 for both day and night conditions of propagation, the experimental values for which are marked by circles and crosses, respectively. The values of the attenuation coefficient over the frequency-range 20–30 kc./s. as measured by Eckersley[8], using signals from long-wave transmitters, are shown for comparison. These follow fairly closely the Austin–Cohen law of attenuation, which predicts a progressive decrease in the value of $\alpha(f)$ as the frequency is lowered but fails to account for the remarkable increase in attenuation at about 10 kc./s. to a maximum value at a frequency of two or three kilocycles per second. The propagation path, in fact, exhibits selective absorption, which, together with the low attenuation at the extreme ends of the audio-frequency range, accounts for the observed long-distance propagation characteristics of atmospherics[1]. As is to be expected, the attenuation at all frequencies is greater by day than by night, but the difference between the day and night values is greatest in the region of maximum absorption.

We recall here the experiments of Gardner[11], who recorded the integrated noise-level of atmospherics using four receivers tuned to different frequencies between 3·5 and 50 kc./s. Gardner found that the ratio of the day to night noise-level was less at 3 kc./s. than at 10 kc./s., from which he inferred that the onset of daylight conditions gave a marked increase of attenuation for frequencies less than 10 kc./s. These conclusions were confirmed by

Bowe[12]. From our observations, it is clear that the greatest increase in attenuation occurs at a frequency of about 2 kc./s., it being then about 10 db. greater than at either 10 kc./s. or at 200 c./s.

It is of interest now to compare our results with those predicted by Budden, assuming propagation in a 'waveguide' bounded by a perfectly conducting Earth and an imperfectly conducting sharply bounded ionosphere. The full-line curves A and B in Fig. 3 are those derived by Budden[13] for the different ionospheric parameters quoted. The attenuation coefficient so calculated as a function of frequency relates to the zero-order mode of propagation, as do our experimentally determined values. The parameter p_r depends on the ratio N/ν where for the upper boundary there are N electrons per c.c., and these are assumed to make an average of ν collisions per second. The orders of magnitude of N and ν for the region in question are 10^3 cm.$^{-3}$ and 10^7 sec.$^{-1}$, respectively; but, as Budden has pointed out, although a small change in p_r does not result in any marked change in the form of his curves, changes in the value of h (the height of the upper boundary) have an appreciable effect. It is also known that the height of reflexion of very long waves is greater at night than by day, and the general agreement between the theoretical and experimental values of $\alpha(f)$ both substantiates the waveguide theory and the experimental method followed in this work. Moreover, the appropriate value of h for these very low-frequency waves can be inferred from the measurement of their attenuation.

The attenuation curves shown in Fig. 3 were derived from atmospherics originating in European storm centres and relate to propagation over the ground. A difference, however, has been found for Atlantic sources giving an appreciable sea-path, the most striking difference being the improved transmission of signals at the higher frequencies, particularly in the region of 5 kc./s. This is undoubtedly an important factor in determining the characteristic type of atmospheric observed from Atlantic sources. Further, the diurnal and seasonal differences in propagation, which will be dealt with elsewhere, clearly follow changes in the ionosphere. For all ionospheric conditions the same type of attenuation curve is obtained. There is a marked selective absorption band, and this is associated with a discontinuity in the group velocity of the waves. Calculations have shown that the group velocity of the atmospheric 'slow tail' component is less than that for the higher-frequency 'oscillatory head', and that in the neighbourhood of the absorption band the group velocity decreases rapidly.

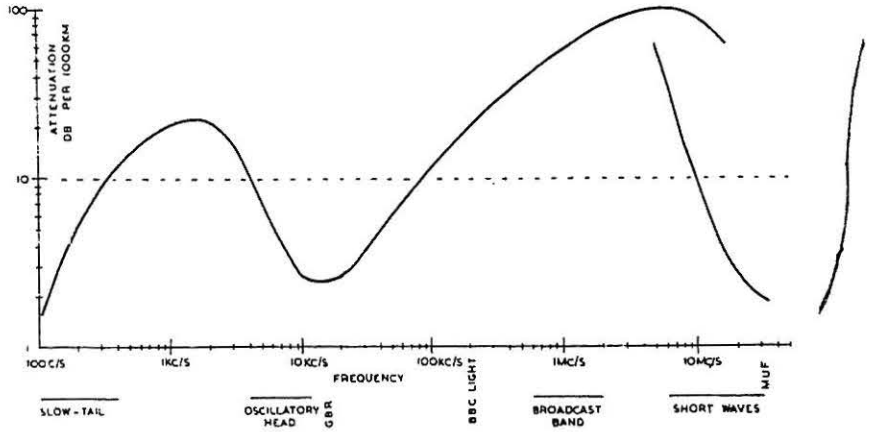


Fig. 4. Variation of attenuation with frequency. The curve for the frequency range 30 kc./s. to 30 Mc./s. is taken from Eckersley (ref. 2, Fig. 31)

Finally, in Fig. 4, we link the results of the work now described with the attenuation curve for long-distance day transmission of radio signals of frequency up to about 30 Mc./s. as given by Eckersley[2]. This curve gives a fair idea which waves are the least attenuated and can travel to the greatest distances. It is a remarkable property of the ionosphere that extremely low-frequency waves less than two or three hundred cycles per second only suffer the same small attenuation as that assigned to the short waves so extensively used in world-wide communication.

The work described here was carried out with the co-operation of the Meteorological Office Sferics Organization for the location of the sources of atmospherics, and without which the investigation would not have been possible. We gratefully acknowledge our indebtedness to the Director of the Meteorological Office and his staff, also to the Department of Scientific and Industrial Research for a grant to cover the cost of equipment.

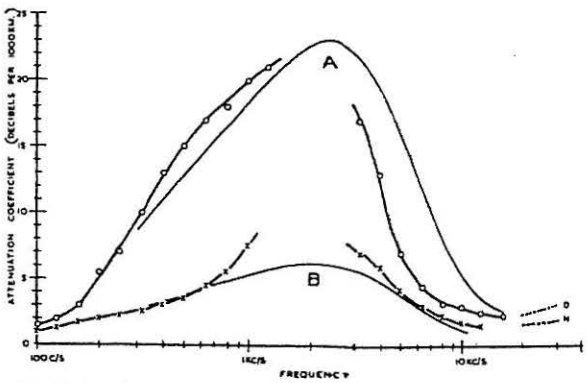


Fig. 3. Variation of attenuation coefficient with frequency for propagation over the ground

—O—O—, Day-time values; —×—×—, night-time values compared with the theoretical curves for different ionospheric parameters; A, ionospheric height, $h = 50$ km., $p_r = 6 \times 10^4$ sec.$^{-1}$, and B, for $h = 80$ km. and $p_r = 2 \times 10^5$ sec.$^{-1}$. Eckersley's values, ...; D, day, and N, night

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Lower Ionospheric Sounding by the Use of Loran-C Signals

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Pulsed 100 kHz radio-signals developed for the purpose of establishing Loran-C navigation systems and timing of clock signals are thought to be a useful tool for the studies of geophysical characteristics of the lower ionosphere below *E* layer.

Timing accuracy of the Loran-C ground waves has been well established to be less than 0.1 μsec for sea surface propagation and less than 1 μsec for land surface propagation and the ground waves have been found to be measured at distances about 3500 km from the transmitter (DOHERTY *et al.*, 1961). Despite of this there have appeared only a few papers that discuss the lower ionospheric characteristics by using these stable signals up to the present (DOHERTY, 1964, 1967, 1968).

We have made at Saku-shima Observatory (137°03′E, 34°43′N) of the Research Institute of Atmospherics a preliminary observation of Loran-C signals propagating the distance 1177 km from the master station at Iwo Jima (141°19′E, 24°48′N) of the Northwest Pacific Loran-C Chain (SS-3), beginning from May 1971 to investigate the geophysical characteristics of the lower ionosphere in the Far Eastern Region of the globe.

The pulsed 100 kHz signals were conveniently used to record one-hop sky-wave separated from ground wave, thus the phase lag of the sky-wave in reference to the ground-wave was continuously recorded during the period. Figure 1 shows the average diurnal phase variation in μsec of one-hop sky-wave for the period from Feb. 2 to Feb. 28, 1972, where sunrise and sunset time on the ground and the ionosphere at the one-hop reflection point (139°17′E, 29°46′N) are indicated with the lines. Ionospheric sunrise and sunset are defined here to be the time of the solar zenith angles of 100°, when the upper limb of the sun, as seen from the *D* region, emerges over the horizon (DOHERTY, 1967). Dotted line indicates the variation of $\sec^{1.2}\chi$ (χ the solar zenith angle).

Indicated on the ordinate is the phase lag of one-hop sky-wave from the corresponding ground-wave, from which the effective ionospheric reflection height is derived by using ray theory. We obtain the minimum reflection height of 69 km at noon and the maximum 88.5 km at mid-night. While the variation of the reflection height in day time correlates to $\sec^{1/2}\chi$, the gradual increase of about 5.5 km in about 5 hr after the ionospheric sunset time at the one-hop

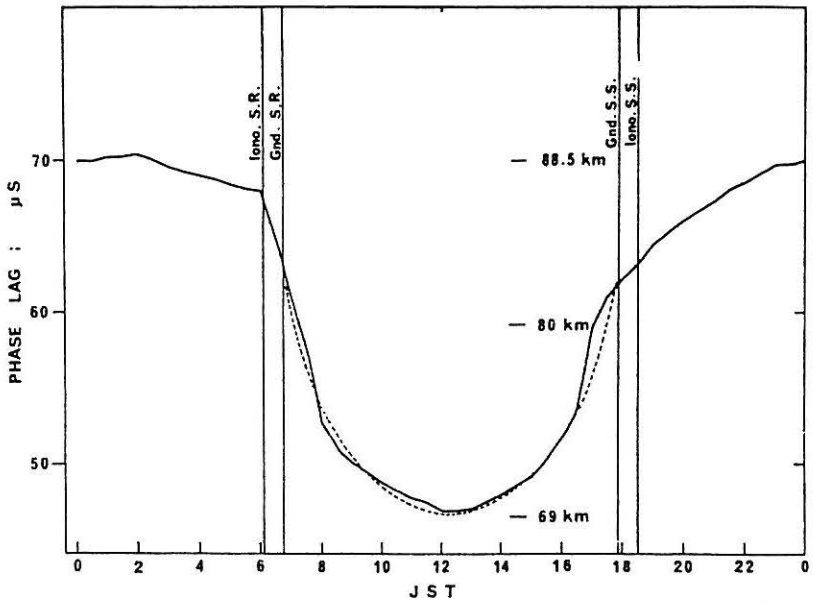


Fig. 1. Diurnal phase variation of Loran-C radio waves. Dotted line indicates the variation of $\sec^{1/2}\chi$ (Averaged value over the period of Feb. 2 to 28, 1972).

reflection point is found to be a little larger and longer than the similar observation results based on the oblique reflection of LF radio-waves by other workers (DOHERTY, 1964, 1967, 1968; BELROSE, 1964). But the nocturnal phase variation observed by the author is similar to the nocturnal amplitude variation observed by DOHERTY (1967), and to the gradual decrease of critical frequency of E region echoes below 100 km in winter obtained from low frequency ionograms (WAKAI, 1968).

The decay time of electron density after dusk caused by the recombination between electron and positive ion is about 30 min at 100 km height (OGAWA and TOHMATSU, 1966). The main source of ionization in the low latitude nighttime D region is the scattered H Lyman α, which ionize nitric oxide and make positive ion and electron.

The intensity of the scattered H Lyman α correlates to the solar zenith angle, and its nocturnal variation is thought to be mainly symmetry with respect to local midnight (DONAHUE, 1966). Therefore, the variation of the reflection height after dusk caused by the intensity variation of the scattered H Lyman α would be of the same amount to the decreasing reflection height before dawn, which is about 1.5 km. If this could be true, the rest variation of about 4 km should be caused by another effect.

One possibility will be the following. The diurnal variations in nitric oxide concentration calculated by SHIMAZAKI and LAIRD (1972) show the gradual long time decrease after dusk at the height of 90 km. The decrease of nitric oxide

concentration will lead to the decrease of ionization by the scattered H Lyman α and bring to the decrease of electron density, if the recombination coefficient between positive ion and electron does not change. Thus the reflection height of radio-waves will gradually be increased. Another possibility is the effect of the variation of ionization source, such as precipitating particles (OGAWA and TOHMATSU, 1966; POTEMRA and ZMUDA, 1972). Further qualitative investigation is needed for the full interpretation of these phenomena. The phase differences are compared between the one-hop and the two-hop sky-waves in reference to the ground-waves, but we do not find it possible to see any appreciable phase difference existing between the two except for those arising from ray path length difference. Thus the phase skip due to the ionospheric reflection is concluded to be negligible.

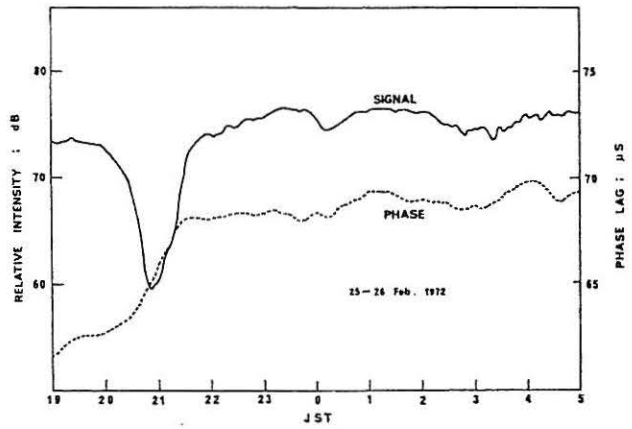


Fig. 2. An example of phase and amplitude variations of Loran-C radio waves in night hours (Feb. 25 to 26, 1972).

Figure 2 shows an example of the phase and amplitude variations in nighttime on Feb. 25 to 26, 1972. The amplitudes are found always fluctuating in nighttime and roughly showing overlapping of the two types of periodic fluctuations, that is, amplitude fluctuations of the magnitudes from 0.5 to 2 dB with the periods from 5 to 20 min and the fluctuations from 2 to 4 dB with the periods from 40 to 70 min. It is found that the larger amplitude fluctuations are usually accompanied by the phase fluctuations, while the smaller amplitude fluctuations are not always accompanied by the detectable phase fluctuations.

Our phase measurements are reliable at more than 0.1 μsec now.

Thus the smaller amplitude fluctuations are thought mainly to correspond to the absorptive fluctuations of 100 kHz radio-waves on the propagation path, which might be interpreted by the irregularities in the lower absorption layer of the two layer ionospheric model, which was proposed by STANLEY (1950) and adopted for the interpretation of LF radio measurements by DOHERTY (1967,

1968). The larger amplitude fluctuations might relate to the variations in upper layer characteristics of the two layer model, which performs the function as a reflection layer. The correlated phase and amplitude measurements on Loran-C radio-waves seems to be very useful for the investigating the dynamics of lower ionospheric irregularities.

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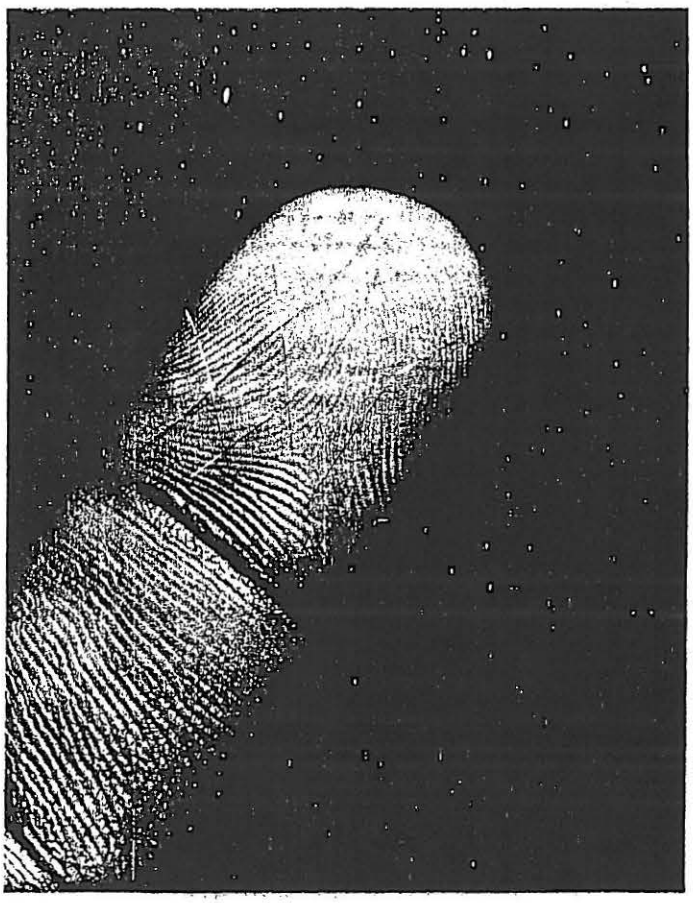
Needles in the Sky: The Strange History of Project West Ford

by Tony Reichhardt

One thing everybody agrees on: "Needles" was a terrible name. It's an unfriendly word, the kind that makes you cringe and start rubbing your arm, right where the hypodermic goes in. It isn't a good description of the West Ford dipoles. And it certainly isn't the kind of word you want to use in public relations. As one survivor of the West Ford controversy puts it, "that's the sort of PR you get when you leave it up to the engineers."

Tom Rogers, one of those engineers who worked on West Ford in that long ago when haircuts were flat and the space program was young, admits it was a blunder. "But in those days, what did I know about politics? What did any scientist know about politics? That was somebody else's job."

One of the people whose job it *was* now says: "All the negative things that have been said about 'Star Wars'? They aren't a drop in the bucket compared to what they said about West Ford."



The infamous "needles": "You couldn't even see the damn things." (Photo: MIT Lincoln Laboratory)

In the summer of 1958, only eight months after a tiny satellite called Sputnik hurled an innocent world into the space age, a group of scientists and engineers, most of them connected with the Massachusetts Institute of Technology, met in a schoolhouse in the town of Barnstable on Cape Cod. They were there at the behest of the U.S. Army Signal Corps, and they were there to come up with ideas. Specifically, the group was asked to spend their summer looking into new methods of sending secret military communications over long distances, as in across the entire United States.

The Signal Corps already had a solid base of experience with sending long distance radio communications via ground terminals, but at the dawn of the satellite era people were starting to look to space for the answers. Within a year after World War II, the Army had begun bouncing radar signals off the Moon, and by the late 1950s, the establishment of the first satellite links in space was well underway, with projects such as SCORE and Courier.

It wasn't a satellite that the Barnstable group dreamed up that summer, however. Walter Morrow of MIT's Lincoln Lab and Harold Meyer, then of the Ramo-Wooldridge Corporation, came up with an idea for another kind of radio relay in orbit—a swarm of millions of tiny copper "dipoles," or hair-thin pieces of wire, that would spread into a narrow belt around the Earth to act as a kind of artificial ionosphere. As long as you beamed up radio signals of the same wavelength as the length of the wires—about seven tenths of an inch—the belt would act as a passable reflector, and you would be able to bounce radio messages from coast to coast.

The concept was absolutely sound, if a bit unusual. "In the laboratory, wild ideas are really looked for, because the possible payoff is great," says Rogers, who was head of the communications division at Lincoln. "Once you start leaving the lab, then it gets more difficult to convince people that it's worthwhile."

But the Barnstable group did manage, in a meeting one Saturday morning after the summer study was finished, to

convince officials of the Air Force Systems Command that the dipole belt concept would work, and the Air Force agreed to pay for tests. One of the strangest chapters in space history was about to be written.

Today we take the principles of satellite communications for granted—a signal goes up, gets turned around by a transponder in orbit, then comes down. But in those days, before Telstar 1 opened the era of commercial satellite communications, there were many questions still unresolved. Was it better to use passive spacecraft like the Echo balloon, a shiny globe that simply reflected radio signals back to Earth? Or was it better to use active transponders? Was it better to put the satellites in high orbits or low?

A couple of hundred miles south of MIT, in Hillside, New Jersey, another team of radio engineers was busy working on a competing method of relaying signals in space. The MIT group was dealing with secret military radio messages, but the AT&T Bell Labs had other fish to fry—they were concerned only with the commercial possibilities of communications satellites. Many of the technical problems were the same, and as Tom Rogers says, "they were every bit as smart as we were."

The one great advantage the dipole belt idea had over the Telstar satellite, at least for the military, was its survivability in the event of a nuclear attack. The belt would actually heal itself if a bomb were to rip a great wound in it—the laws of orbital physics would see to it that the individual dipoles closed the hole again to make a neat ring around the Earth. You couldn't make the same claim for relay satellites, and in fact, Telstar 1's life was later cut short by the effects of an atmospheric bomb test.

It was this survivability factor that had the Defense Department interested in Lincoln Laboratory's research. "We weren't doing it to check out the temperature of the upper atmosphere," says Rogers.

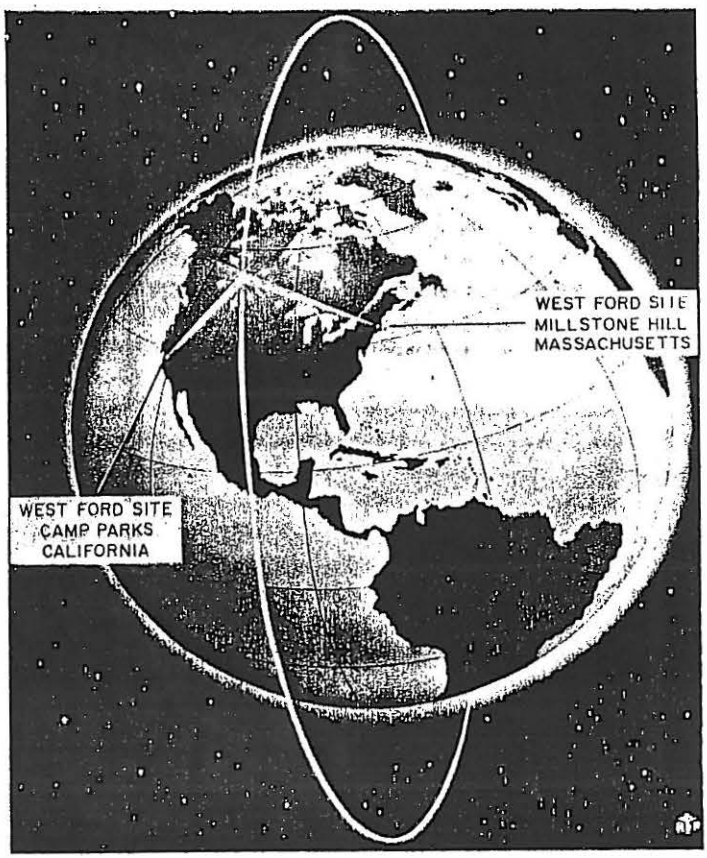
The project started off as classified, and the MIT people set to work building two 60-foot X-band radio antenna dishes—a considerable technical accomplishment in its day—near Westford, Massachusetts and across the country in Camp Parks, near Pleasanton, California.

For the initial test, the dipoles were to be launched piggyback on an Air Force satellite into a 2000 mile-high orbit. A little dispenser would pop out, with some 480 million dipoles embedded in naphthalene (the same stuff mothballs are made of). As the naphthalene evaporated in orbit, the spinning disks would spit out the individual dipoles, which would spread out into a uniform belt in a matter of weeks. The entire belt, about nine miles wide and fifteen miles deep, circling the poles of the Earth, added up to only about 40 pounds of copper.

By 1960, the MIT engineers were going at their new project hammer and tongs, six or seven days a week, remembers Rogers. "We were all in our twenties and thirties, and we were taken with this as a scientific problem. We were completely insensitive to political considerations."

Witness the project's name. Somehow, nobody remembers just how, it got to be called "Needles" within the lab. "The original name took us a day," says Rogers. "Some technician said 'They look like needles to me,' and we said 'Needles' is alright, why bother? We never gave it a thought."

But a plague was soon to descend on the house of the Needles Project, in the form of angry protests that eventually reached as high as the President's science advisor, the United Nations, and editorial pages around the world. Two years later, when the folks at Bell Labs finally launched Telstar 1, their new satellite had everyone all misty-eyed



The concept was absolutely sound, if a bit unusual. Radio signals beamed from one coast would be reflected from a nine-mile-wide dipole belt in orbit to be picked up by another antenna across the country. (Photo: MIT Lincoln Laboratory)

about the future, and the beach-sound guitars of The Ventures jangled out a hymn for the New Frontier. Well, nobody ever wrote a song about the West Ford needles. But man, did they wail.

The loudest shrieks came from the astronomical community, some of whose members were convinced that a belt of copper needles around the Earth would ruin their view of the universe, either at radio frequencies or optical wavelengths, or both. And if the testing didn't ruin things, then it would just open the door for the military to put all kinds of junk up there that would blind the astronomers' telescopes.

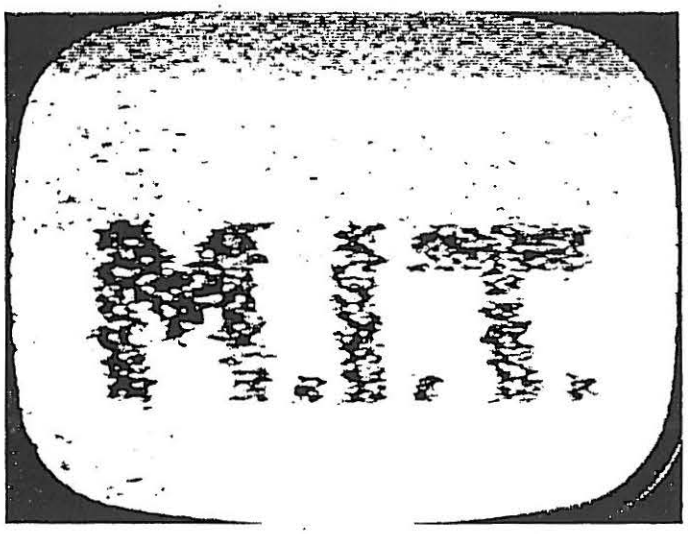
The protests were serious, even though the individual dipoles would be separated from each other by about *a quarter of a mile* in orbit. And they were so *tiny*—each copper wire was only one fifth as wide as a human hair and less than an inch long. Words like "needle" and even "dipole" are way too substantial for these little pieces of fluff. When you held them in your hand, said an MIT public affairs officer, "you couldn't even see the damn things."

Accustomed to fighting for clear skies, (the Echo balloons already had scientists nervous, particularly when people began talking about putting up *thirty* or more of the shiny globes to criss-cross the heavens) the astronomers blasted away at the Needles Project. John Findlay, who headed a committee of the National Academy of Science's Space Science Board to look into the matter, remembers a meeting in June 1960 that took place around a swimming pool near Los Angeles, in which members of the Board argued about the Needles project far into the night.

fighting the howling devils of controversy. By this time, the project had been de-classified, but newspapers were still writing of the "super-secret Needles project." At the same time, recalls one ex-staffer, the West Ford PR department was pumping out press releases explaining the project, using language like "soft as bunny hairs" to describe the dipoles, or photos that compared them to a kitten's whiskers—anything that might allay the fear that these were sharp, menacing needles. Still, the storm raged, right up until the second test launch.

That came on May 8, 1963. Some 480 million copper dipoles were released into orbit 2000 miles above the Earth at 4:57 Pacific Daylight Time on May 10. The dispenser ejected the needles correctly this time, but as the swarm began to expand, it was clear that the individual dipoles were not spreading out exactly as intended.

Because the launch had been delayed for some fifteen or twenty minutes—nobody remembers why, or even what the military payload launched that day was—the Sun did not hit the canister at exactly the planned angle, which caused more than half of the dipoles to come off in clumps rather than as individuals. A belt did form, however, and had closed around the Earth by June. Successful relay tests were conducted in the following weeks, and although they were degraded by the clumping, the communications experiments worked more or less to specification.



During the week of April 22, 1962, Lincoln Lab sent the first television pictures via satellite, using the powerful West Ford antennas in California and Massachussetts and the nearly deflated Echo balloon in orbit. It was nearly three months before the launch of Telstar 1. (Photo: MIT Lincoln Laboratory)

For a few months following New Year's Day, 1966, a soft copper snow fell all over the Earth—hundreds of millions of tiny West Ford needles coming back home.

The White House had decreed in 1961 that no further tests of the West Ford concept would be made until everyone had had a chance to fully analyze the results. Astronomers all over the world strained to find evidence of interference, but search as they might, not even the most powerful telescopes could see the dipoles (despite one or two photographs of the concentrated swarm taken shortly after the needles were released). In 1964, project engineers Walter Morrow and Irwin Shapiro could write confidently that the dipoles "never interfered with any astronomical observations."

By then, though, the handwriting already was on the wall—Telstar-type satellites were clearly the wave of the future as far as space communications went, and the West Ford concept was quietly and without much ado laid to rest.

In a fascinating paper in the December 16, 1966 issue of *Science*, Irwin Shapiro described what happened to "The Last of the West Ford Dipoles." It was Shapiro who had come up with the idea of placing the needles in such an orbit that the Sun's delicate radiation pressure and atmospheric drag would cause them to fall back down to Earth after only a few years (one of the experiment's ground rules was that the belt had to come *down* after the tests were over.)

For a few months following New Year's Day, 1966, a soft copper snow fell all over the Earth—hundreds of millions of tiny West Ford needles coming back home. "Unfortunately," Shapiro wrote, "New Year's celebrations were not punctuated by a display of tiny fireballs," since the dipoles were too small even to radiate enough heat to burn up in the atmosphere.

Despite the mail from people all over the world, including a woman in Indiana who claimed to have found a West Ford needle on her dining room table, and a person in New Zealand who carefully wrapped and mailed in a piece of copper found on a plant, none of the dipoles have ever been found.

Shapiro calculated in his paper that the maximum density of falling dipoles would occur at the poles, but even there you would only find about five in every square kilometer, and he wisely dismissed the notion of mounting a search expedition to dig through Arctic snow for tiny copper hairs. Although Shapiro believes a few clumps of needles are probably still up there in orbit, for all practical purposes the end of the West Ford saga came with that invisible copper snow in 1966.

Today, Shapiro heads the Harvard-Smithsonian Center for Astrophysics in Cambridge. Walter Morrow is Director of the Lincoln Laboratory, and half a dozen others who worked on the project have gone on to prominence in the space program. Inured by Chernobyls and *Challengers*, they've become accustomed to skepticism and public protest over what The Scientists and The Engineers are doing. But back in 1960 it was different. "This was the first time many of us had run into controversy over technology," says Morrow.

Tom Rogers is now an influential private consultant who pursues a feisty dedication to the idea that more people should eventually be offered the opportunity to travel into space. Of the West Ford years, he says: "You felt you were cutting ground. Everything you did was new." Rogers looks a little wistful. "Those were the halcyon days of the space program." ★

Subsurface Radio Propagation Experiments[1]

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Propagation experiments were conducted on Cape Cod, the Adirondack region of New York State, and in Cheyenne Mountain in Colorado to determine the feasibility of communication between vertical linear antennas located in drill holes in the rock below overburden, and similar antennas located on the surface of the ground.

The bulk conductivity of the propagation media, i.e., the average conductivity along the path between the antennas, must be determined by measurements of propagation loss and transmission delay, because of the lack of homogeneity in the rock media. High values of bulk conductivity limited experiments to the VLF region on Cape Cod and the Adirondacks, which involved ranges of 1.6 km and 5 km, respectively. Distances up to 48 km in the LF region were achieved by up-and-over transmissions from inside Cheyenne Mountain.

Analysis of the experimental results and theoretical considerations indicate that the usefulness of the through-the-rock mechanism is severely limited by the bulk conductivity. For shallow antenna depths, particularly if the overburden is thin or absent, substantial transmission ranges can be achieved by using up-over-down propagation.

1. Introduction

There has been considerable interest recently in the possibility of using subsurface rock strata for hardened radio communications. With both transmitting and receiving antennas situated in the bedrock below the surface of the earth, propagation can be achieved directly through the rock medium between the antennas. Through-the-rock propagation has been the principal concern of a series of investigations on Cape Cod, and in the Mineville and Black River areas located in northern New York State. The "up-and-over" mechanism was also investigated in the Cheyenne Mountain area in Colorado, between an antenna buried deeply in the rock and an antenna located on the surface of the ground. This paper reviews the various techniques and summarizes the experimental results obtained in the course of these investigations.

Many programs of theoretical and experimental investigations in this field have been conducted in the past. References cited here are but a small portion of, or addition to, the bibliography to be found elsewhere. To cite but a few publications, Hansen (1963) gives an excellent survey that considers up-over-and-down propagation. Ames, et al. (1963) consider the potential of communicating via direct through-the-rock transmission. Biggs and Swarm (1963) treat the fields in air from a buried antenna to antennas on the surface or elevated in the air, neglecting the influence of the ionosphere; this can be designated the up-and-over mechanism. Wait (1963) develops the idea of a wave guided in a low-loss horizontal layer in the earth's crust. A thorough review of progress on the subject is presented by deBettencourt (1966).

2. Experimental Arrangements

In conducting through-the-rock propagation experiments, access to the rock is made by drilling vertical holes through the overburden and into the rock. Vertical linear antennas are placed in the holes below the conducting overburden as shown in figure 1. Since the overburden generally is more conducting than the rock below, the overburden serves as a reflecting ground plane, allowing monopoles to be driven against it. The antennas are connected by transmission lines to the transmitter and receiver located on the surface of the ground. The properties of antennas in drill holes are discussed in detail by deBettencourt and Sutcliffe (1962).

For these experiments a 100-W audio amplifier was used as a transmitter, and either a low frequency communication receiver or a narrowband wave analyzer was used as a receiver. The magnitudes and phase angles of mutual impedances between the transmitting and receiving antennas were obtained through measurements. From these, the bulk conductivity, i.e., the average conductivity, of the medium between the antennas was deduced. The length of the antennas in the drill holes varied from the 150-m

[1]This work was sponsored by the Air Force Cambridge Research Laboratories under Contract No. AF19(628)-2362 and, in part, by the Raytheon Company, Norwood Mass.

antennas used on Cape Cod to 600-m antennas used in New York.

Initial experiments conducted at Brewster, Massachusetts, on Cape Cod used two drill holes 300 m deep, separated by 1.6 km (Tsao, 1963). Transmissions were made at frequencies below 7.5 kHz. Later, measurements were made in the Mineville area in New York State, where two existing deeper drill holes, separated by 1.6 km, were used as antenna sites for transmissions at frequencies up to 50 kHz (Tsao, 1964a). Subsequently, based on results obtained in the Mineville area, and also from supporting data from a surface resistivity survey, two drill holes were made available to establish a 5-km path in the Black River area in New York State, where transmissions were made at frequencies below 100 kHz (Tsao, 1964b).

Later, experiments were conducted in the Cheyenne Mountain area of Colorado to investigate the up-and-over transmission (Tsao, 1965). As shown in figure 2, a transmitting antenna was placed in a slanted drill hole such that the antenna was parallel to and about 210 m below the eastern slope of Cheyenne Mountain. Access to the drill hole was made at Turnaround, a point along a tunnel road leading into the NORAD complex. The antenna orientation was selected to favor up-and-over transmission to surface points located east of the transmitting antenna.

3. Experiments and Results of Subsurface Transmissions

3.1. 1.6-km Transmissions on Cape Cod

On Cape Cod, transmissions were made at frequencies below 7.5 kHz over the 1.6-km path between antennas inserted in the 305 m deep drill holes (Tsao, 1963). Figure 3 shows the magnitude of the mutual impedance, i.e., the magnitude of ratio of the voltage induced in the receiving antenna to the current at the input terminal of the transmitting antenna. It is seen that the magnitude of the mutual impedance is constant at the lower end of the frequency scale. This is because the electrical distance between the antennas is short, and only the quasi-electric field is important. (In this case, the mutual impedance does not have an inductive component and can be referred to as the mutual resistance.) As the frequency increases, the electrical distance increases. Hence, the magnitude of the mutual impedance decreases rapidly, due to the increased importance of the exponential damping in the far field zone.

The measured phase angle of mutual impedance as a function of frequency for the Cape Cod path is shown in figure 4. The square root dependency of phase angle to frequency indicates that the rock

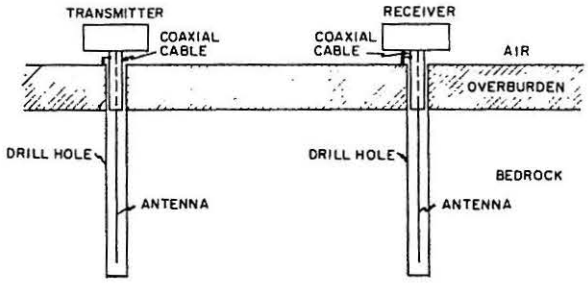


FIGURE 1. *Schematic configuration for through-the-rock propagation experiments.*

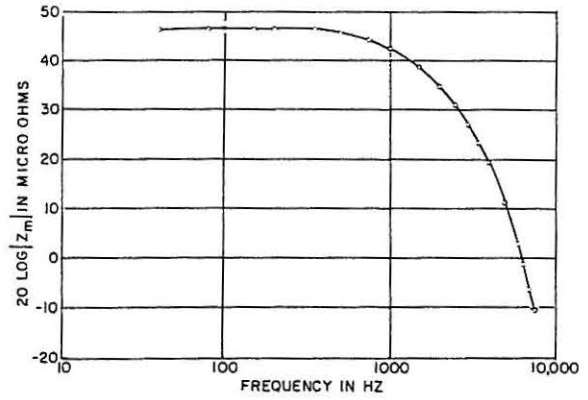


FIGURE 3. *Mutual impedance vs. frequency, 1-mile path, Cape Cod, Mass.*

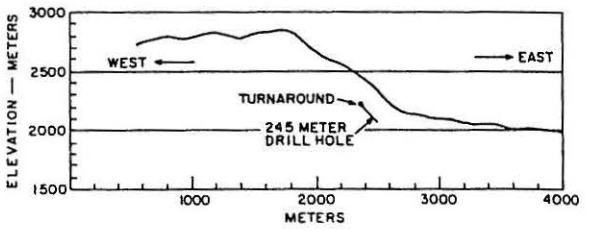


FIGURE 2. *East-West cross section of Cheyenne Mountain through Turnaround.*

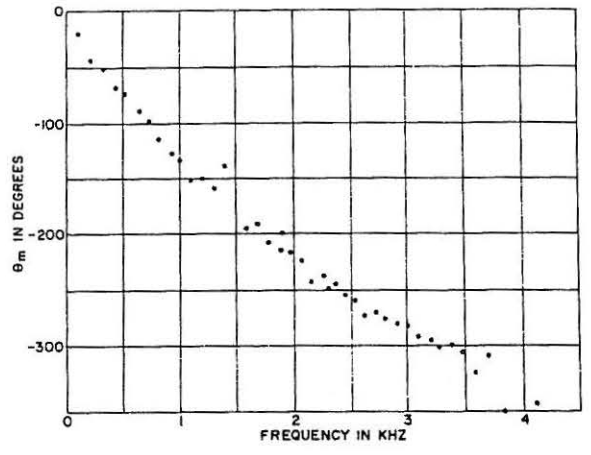


FIGURE 4. *Measured phase angle of mutual impedance, 1-mile path, Cape Cod, Mass.*

medium along the path has a large loss tangent. Measurement of the phase angle of the mutual impedance requires the use of common reference phases at both the transmitter and the receiver. On Cape Cod, this reference was derived from a LORAN C transmission originating on Nantucket Island (Tsao and deBettencourt, 1967).

The bulk conductivity of the rock for the 1.6-km path on Cape Cod was deduced from the amplitude and phase data independently, and was found to be approximately 1×10^{-3} mhos/m.

3.2. 1.6-km Transmissions at Mineville, New York

Measurements of amplitude and phase of the mutual impedance were also made at Mineville between antennas in deeper drill holes 1.6-km apart. At Mineville, measurements were made at frequencies up to 50 kHz (Tsao, 1964a). From these measurements, the attenuation and phase constants of the propagation medium were deduced as shown in figure 5. At the lower frequency, the attenuation and the phase constants are equal and proportional to the square root of the frequency due to the large loss tangent. At frequencies near 50 kHz, as the loss tangent becomes small the phase constant becomes greater than the attenuation constant. Using a curve-fitting method, these data provided a bulk conductivity of 2.5×10^{-4} mhos/m and a relative dielectric constant of 48. The corresponding theoretical attenuation and phase constants are shown by the solid curved lines in figure 5.

3.3. 5-km Transmissions at Black River, New York

Transmission tests over a 5-km path were made between drill holes in the Black River area (Tsao, 1964b). Only the magnitudes of the field intensities were measured. Field intensities measured in air and in the hole at the receiving site (Wadhams, N.Y.) are shown in figure 6.

In the Black River experiment there is strong evidence that at frequencies above 50 kHz, signals were received due mainly to propagation through the air, i.e., the up-over-down or up-and-over mechanism. This is shown in figure 6 by comparing the measured field intensities with the estimated strengths of signals in air and in the earth, as shown by the solid and the dashed curves, respectively. There is equally strong evidence that at frequencies below 50 kHz, the signals received in the hole were primarily due to the direct or through-the-rock propagation. The bulk conductivity in this area was found to be about 8×10^{-5} mhos/m.

3.4. Transmission From Inside Cheyenne Mountain

Following the experiments described above, propagation tests were made in the Cheyenne Mountain area to determine whether transmissions could be made from inside Cheyenne Mountain to receivers on the surface east of the mountain (Tsao, 1965). The through-the-rock transmission was not attempted in this area. An antenna buried 210 m below the surface of Cheyenne Mountain (fig. 2) was used for transmission; measurements of field intensity were made on the surface of the ground. The transmission path was only partially through rock.

Measurements of surface field intensities due to transmission from inside Cheyenne Mountain were made along several 50-km radials from the transmitter, at a frequency of 70 kHz. The measured field intensities, normalized to 1 A of input current to the transmitting antennas, are shown in figure 7. The field intensity along each radial varied inversely with distance. The inverse distance dependency is characteristic of groundwave propagation for the frequency and distances involved, because the ground attenuation is negligible. The bulk conductivity of the rock surrounding the buried antenna was estimated to be about 3.5×10^{-4} mhos/m.

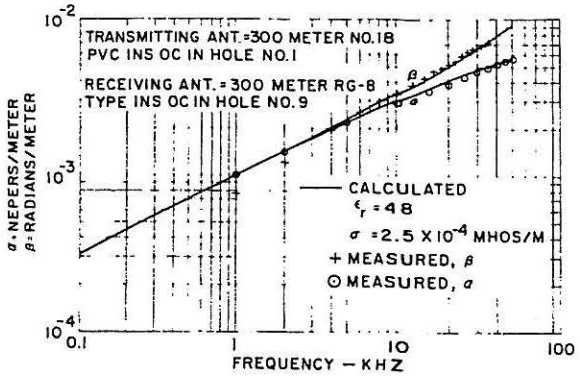


FIGURE 5. *Attenuation and phase constants vs. frequency, 1-mile path—Mineville.*

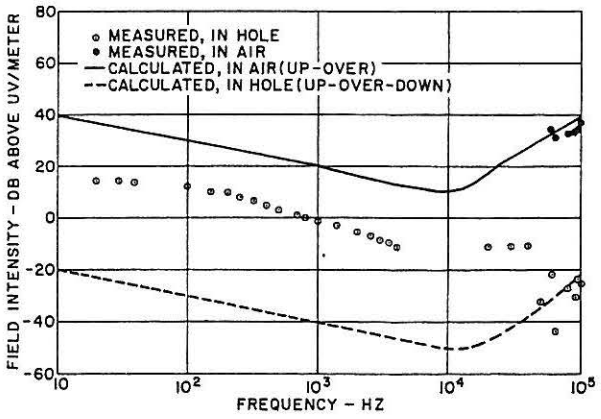


FIGURE 6. *Vertical field intensities, 3-mile transmission path at Black River.*

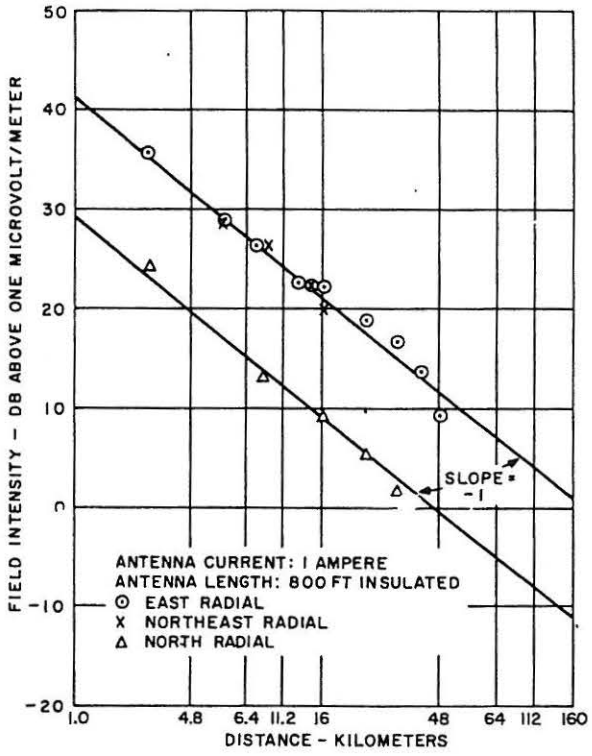


FIGURE 7. *Surface field intensity at 70 kHz due to transmissions from inside the mountain.*

3.5. Comparison of Conductivity Values Deduced From Transmission Tests and Surface Resistivity Measurements

The conductivity and layer thickness of a horizontally stratified region of the earth's crust can be deduced from measurements derived from the surface resistivity method. In this method, the apparent resistivity (conductivity) of the earth located below horizontally polarized transmitting and receiving dipoles located on the earth's surface is deduced from measurements of mutual impedance, i.e., the ratio of voltage induced in the receiving dipole to the current in the transmitting dipole. Various dipole configurations may be used. As the dipole spacing is changed, the apparent resistivity may vary in a manner to indicate the presence of several layers. The variation of apparent resistivity with the separation of the dipoles provides the skilled analyst with the magnitude of the conductivity and the thickness of the several layers. Horizontal dipole separations are comparable to, or exceed, the range of depths desired. Past measurements used direct current; recently, alternating currents of a fraction of a Hertz to several Hertz have been employed.

Surface resistivity experiments using frequencies of less than 1 Hz were conducted on Cape Cod and in northern New York State (Cantwell and Nelson, 1963). These measurements were intended to obtain deep resistivity data for correlation with the bulk conductivity data obtained from the more involved transmission tests described above.

Surface resistivity measurements on Cape Cod yielded rock layer conductivities of 1.7×10^{-4} to 2.7×10^{-4} mhos/m, depending on the variation in the estimates of the thickness and resistivity of the overburden. The bulk conductivity was found to have a much higher value of about 1×10^{-3} mhos/m, as deduced from the rock strata radio propagation tests.

At Mineville in northern New York State, the data from surface resistivity measurements showed serious scatter and were considered unusable for simple interpretation. This difficulty was attributed to the geological inhomogeneity in the area. Nevertheless, radio transmission tests provided a measurable bulk conductivity of 2.5×10^{-4} mhos/m.

At Black River, also in northern New York State, the geology was considered more homogeneous than at Cape Cod or Mineville. Surface resistivity measurements at Black River yielded a rock conductivity of 5×10^{-5} mhos/m. This agrees well with the bulk conductivity of 8×10^{-5} mhos/m, determined from the through-the-rock radio transmission measurements.

Apparently, surface resistivity measurements are primarily useful in regions that consist of simple homogeneous layers. Analysis of data is quite difficult if there is severe lateral inhomogeneity in addition to horizontal layering in the geology, since interpretation of the data depends on evaluation of the variation of apparent resistivity with dipole-to-dipole separation. There is, however, an important advantage in using this method; because of its simplicity and with no requirement to drill deep holes in the rock, it could be used as a tool for obtaining preliminary information on the rock strata conductivity data. However, bulk conductivity of a through-the-rock path should eventually be determined directly through subsurface propagation measurements.

4. Discussion and Conclusion

4.1. Separation of Transmission Modes

In experiments to test the transmission of signals through the subsurface rock medium, it is always of special concern to the experimenter and others whether the received signal actually followed the through-the-rock path instead of some other path such as the up-over-and-down path, transmitter leakage, or radiation from transmission lines.

The effects of transmitter leakage and poor receiver shielding may be simply evaluated by replacing the antennas with dummy loads, to determine the extent of spurious radiation and pickup. In the through-the-rock propagation experiments described above, there was no evidence that the tests were so contaminated.

Measurement of relative field intensities in the air and in the ground is the simplest of the many possible tests to determine whether propagation was achieved

through the rock directly, or by the up-over-and-down transmission.

In the Black River experiment, as an example, the magnitudes of up-and-over and the up-over-and-down signals in air and in rock were estimated from the overburden transmission losses at the transmitter and receiver terminals. This loss was deduced from simultaneous measurements of the vertical electric field strengths of the atmospheric noise in the hole and in the air (Tsao, 1964b). Figure 8 shows the ratio of the field strength of atmospheric noise in the air to the field strength of such noise in the hole. From these experimentally deduced losses, the signals in air (up-and-over) and in the hole (up-over-and-down) at the receiving terminal were estimated as shown in figure 6. Comparison of these estimated signal strengths with the measured values affords a means of determining the relative importance of the up-over-and-down transmissions and the rock propagated signals.

Aside from the measurements of relative field strengths of a signal in air, on the surface, and in the rock below it (due to a remote, buried antenna) the rock propagated signal can be readily distinguished from the up-over-and-down signal by the phase delay along its path, as measured in the experiments at Mineville, N.Y., and on Cape Cod. The large phase delays can only suggest transmissions through a dissipative medium.

The slopes of the attenuation and phase constants deduced from mutual impedance measurements generally indicate the main characteristics of the transmission media. Another possible observation is the phenomenon of depth gain, which is associated with propagation in a rock medium in much the same way as height gain is associated with propagation in air (Carolan and deBettencourt, 1963). The depth gain experiment was conducted on Cape Cod. Short dipoles were used for transmitting and receiving in two drill holes separated by 1.6 km. Antennas were installed at the same depth. Field strengths at the receiving antenna were measured as a function of depth of both antennas. Figure 9 shows the resultant field strengths at various frequencies relative to the magnitude at 1 kHz, with the antennas just below the overburden. An enhancement in field strength is noted for increased antenna depth, and this enhancement is greater at higher frequencies.

4.2. Potential Application to Subsurface Communication

The results of the subsurface propagation experiments indicate that through-the-rock propagation can be used for transmission between antennas buried in rock. The useful range for this type of transmission is limited and decreases rapidly with increased rock conductivity. Furthermore, the useful frequency range is very small. The range and frequency limitations are caused by the exponential damping of the lossy medium.

In addition to the transmission path through rock, propagation may also take place through the up-over-and-down mechanism. Here the depths of antennas

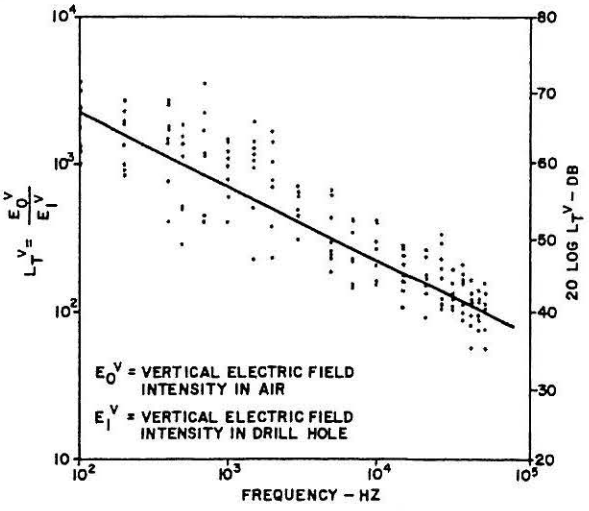


FIGURE 8. *Overburden transmission loss for vertical electric field at Black River drill hole, N.Y.*

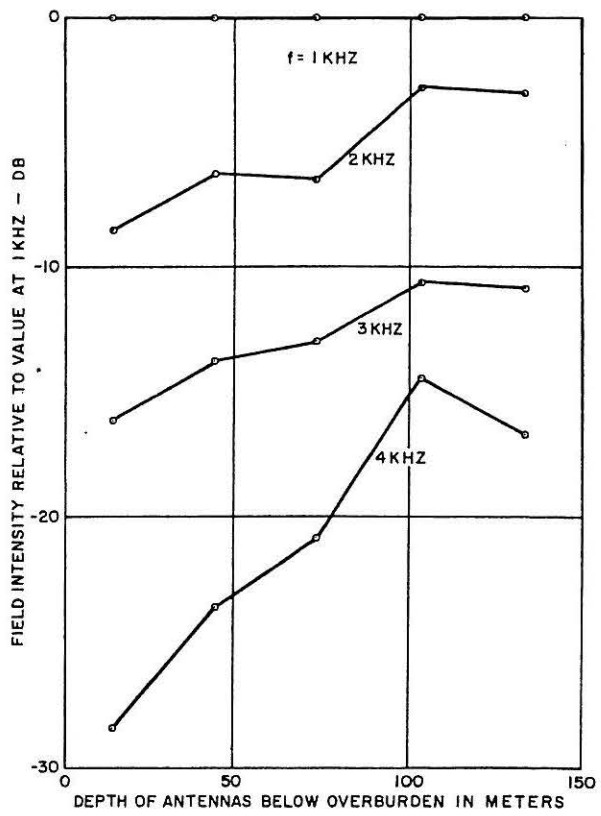


FIGURE 9. *Relative depth gain vs. depth, 1-mile path, Cape Cod.*

below the surface become important, as the exponential damping increases rapidly with antenna depths and frequency. However, the up-over-and-down mechanism suffers refraction losses near the terminals of the path; these losses decrease inversely with the square root of frequency.

The relative importance of the two transmission mechanisms depends on the following factors: separation between antennas; antenna depths below the surface; antenna orientations; the electrical characteristics of the earth. The through-the-rock signal is maximized with transmitting and receiving electric dipoles erected parallel and broadside to each other. The up-over-and-down transmission is best with antennas erected coaxial and parallel to the surface.

The advantage of the up-over-and-down transmission will be enhanced with increased transmission range, because of the additional exponential damping of the longer path through the rock. However, if the rock is separated from the air by a thick layer of highly conducting overburden, its shielding effect will greatly increase the total propagation loss for the up-over-and-down signal, but will have negligible effect on the rock propagated signal. Furthermore, the reception in an up-over-and-down transmission will likely be limited by atmospheric noise. Although increasing the depth of the receiving antenna will reduce the noise level, the up-over-and-down signal will also be reduced by the same amount.

In the subsurface experiments described in section 3, these limitations were aggravated by the relatively shallow depths of the antennas and the lack of sufficiently thick overburden. These factors combined to make the reception subject to serious interference both from atmospheric noise and from signals which entered through the air. Insofar as the future use of the through-the-rock transmission is concerned, much depends on the requirements for using subsurface antennas, on the further development of geophysical techniques to locate low conductivity rock strata deep below the surface of the earth, and on the economics involved in placing antennas at greater depths. (It should be noted that there is theoretical evidence for a waveguide mode of transmission in a layer of very low conductivity bounded by more conducting layers (Wait, 1963). We have not encountered the low conductivities required for such a low-loss mechanism in our measurements.)

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(Paper 3–11–465)

Observations of Natural ELF and VLF Electromagnetic Noises by Using Ball Antennas

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(Received September 25, 1966)

Abstract

A simple observing system for the measurements of vertical electric field component of natural ELF and VLF electromagnetic noises by using ball antennas is described. With this system it is possible to measure long traveled natural ELF noises discriminated from natural local noises due to such as atmospheric electric space-charge fluctuations. Some of the typical recorded noises are shown. Observed ELF noises are divided into three characteristic types; "ELF flash", "ELF burst" (N-and Q-types), and "ELF continuous". ELF flashes originate from the lightning discharges in the area within about 1,000 km from the observing station. Occurrences of ELF bursts are more frequent in the daytime than in the nighttime, and are characterized by sudden increase at the time of local sunrise, suggesting the related mechanism of their generation to the solar position relative to the earth. N-type bursts are followed by VLF noises. Source distances of these bursts which are followed by tweek-type atmospherics in the night are estimated to be in the range from 2,500 km to 5,000 km. Q-type bursts often show clear oscillations of the frequencies of Schumann resonances. The daily variations of the mean amplitude of "ELF continuous" which composes the background noises are quite similar to the daily variations of the world thunderstorm activity.

1. Introduction

In recent years a number of workers have investigated natural ELF phenomena in the electromagnetic waves from different points of interests. Some workers are interested in the study of propagation of ELF radio waves from distant lightning discharge as a source. Other workers are interested in the study of the relation of ELF noise origin to the worldwide thunderstorm activity. Since Schumann (1952 a, b, 1957) presented the resonance theory that FLF electromagnetic waves resonate in the cavity between the good conducting earth and ionosphere, a number of experimental investigations were made to detect actual resonant frequencies in natural electromagnetic phenomena (Balser and Wagner, 1960; Polk and Fitchen, 1962; Chapman and Jones, 1964; Gendrin and Stefant, 1964; Rycroft and Wormell, 1964; Hughes, 1964).

ELF phenomena, however, do not seem to be completely understood, because the typical recorded noises shown in the literatures are not consistent with each other. Some workers recognized that the resonated signals are hidden in the background noises and they appear only by frequency analysis of measured noises (Balser and Wagner, 1960; Madden and Thompson, 1965), while some others clearly showed characteristic oscillations in the meas-

GPs are Pc 3, 4, 5 rather than Pi.

In the cases where the GPs are type Pi and occur during substorms, there is evidence that precipitation pulsations can leave an imprint on both the GP and ELFIM spectra. If there is a dominant frequency in the precipitation pulsations, this frequency may be enhanced in the Pi spectrum if it is close to the resonance frequency of a Pi source current loop (CHAO and HEACOCK, 1980), and this frequency may be imprinted on the ELFIM spectrum through modulation of the attenuation on the ELF waves. It was noted that the ELFIM power spectra for the different frequency bands of ELF are usually very similar: this feature is consistent with significant attenuation spectra, though other explanations are also possible.

It is desirable that this investigation be extended by the acquisition of a larger collection of riometer pulsation data, preferably involving conjugate sites.

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that are generated by 3-dimensional current loops. Such a mechanism for generating Pi has been proposed (WILHELM *et al.*, 1977; HEACOCK and CHAO, 1980; CHAO and HEACOCK, 1980). In the general case, the Pi activity is produced by a number of current loops operating simultaneously, each with time-varying inductance, capacitance and resistance, and each with a driving function (electric field) spectrum that is time-varying. It is seen that Pi thus generated would normally contain many frequencies not present in the spectra of simultaneous ELFIM and precipitation pulsations. However, a dominant frequency in precipitation pulsations can result in an enhancement in the Pi spectrum at that frequency because of the modulation of resistance in the ionosphere leg of the current loop (CHAO and HEACOCK, 1980).

Referring to the September 28 event, which coincided with a substorm, the GP activity seems to be of Pi form (Figs. 1, 3). The GP spectra do indeed contain frequencies not present in the ELFIM or RP spectra, and we may apply the above discussion in explanation. The peaks on the RP spectrum do not generally correspond to resonance frequencies of the Pi current loops (CHAO and HEACOCK, 1980).

Note that the pulsation onsets in GP, RP, and ELFIM are approximately simultaneous near 1814 UT (Fig. 1), which is the onset of the substorm. The occurrence of the three phenomena is due to the availability of substorm electrons in the morning sector, i.e., the trapped electron flux drives the electron cyclotron instability and thus ELFIM, the precipitating electrons explain the RP and the decreased resistance in the ionosphere results in increased amplitudes in Pi and also electrons are provided for field-aligned currents in the 3-dimensional current loops.

In the June 19 case (Fig. 4) the GPs were of Pc rather than Pi form, providing a more favorable situation for occurrence of the CKH mechanism. Certain features in the data, e.g., the Pc 5 peak in the June 19 spectra, are consistent with occurrence of CKH in agreement with the finding of SATO and KOKUBUN (1980) for Pc 3–4 and ELFIM.

5. Summary

A precipitation pulsation event occurring on September 28, 1978, was accompanied by modulations on the intensities of ELF noise at the same periodicities and with wave envelope minima corresponding to absorption maxima, consistent with the ELF noise being modulated by the variations in electron density in the ionosphere.

Two storm sudden commencement events were presented. One had a spike of ELF noise at the SSC, followed by a significant riometer absorption event which seemed to mask away the subsequent ELF. The other SSC had no riometer absorption following, but had clear ELF activity following. Thus, these events are consistent with the September 28 event in implying that the attenuation spectrum is significant.

ELF with intensity modulations are often observed in the morning sector during substorms simultaneous with geomagnetic pulsations of type Pi. The simultaneous occurrences of ELFIM and GPs during substorms may be due to the availability of energetic electrons as required for the generation of these two phenomena rather than to wave and particle interactions involving the GP and ELF. However, the data do not preclude the existence of wave and particle interactions, especially in events where the

We processed many events for which only GP and ELFIM data were taken, and the results were consistent with the existence of complications of the sort mentioned above. Some cases of simultaneous GP and ELFIM were recorded with no evidence of a meaningful relation between the two kinds of wave data, and in some cases there were certain common spectral peaks among many apparently independent spectral peaks. Here, it seems advisable to focus attention on the events for which simultaneous RP data were taken.

The two SSC events were consistent with the September 28 event in that the presence and absence, respectively, of post-SSC ELF events could be due to the absence and presence, respectively, of significant post-SSC riometer absorption. Further, the spike of ELF at the SSC in the September 29 case can be qualitatively explained in terms of time required for build-up of ionization in the ionosphere (ROBLE and REES, 1977). The build-up time is not relevant in the determination of the phase relation of riometer pulsations, i.e., the phase in the riometer data corresponds to the phase of ionization density variations in the ionosphere rather than to the phase of the incident electron precipitation pulsations. Additionally, we note that our riometer pulsation data do not disclose pulsations at frequencies above a fraction of a Hz, whereas balloon X-ray data have showed the existence of precipitation pulsations at frequencies higher than 1 Hz (PARKS *et al.*, 1968). This difference is mainly due to the fact that build-up and decay times effectively smooth out the electron density pulsations that were produced by precipitation pulsations at 1 Hz or higher.

Referring to ELF data published by satellite investigators, it is reasonable to suppose that the typical ELF event observed on the ground has a significant source spectra in ELFIM, i.e., there is usually a significant component of the ELFIM spectrum that is not explainable in terms of ionospheric attenuation of the ELF. Thus, the typical ELFIM spectrum appears to be a mixture of source and attenuation spectra. In the cases of most events that we recorded, the comparisons between ELFIM, RP, and GP are so complex as to defy separation of source and attenuation spectra. In some cases, however, certain spectral peaks on the ELFIM spectrum correspond to peaks on the GP spectrum, while others correspond to peaks on the RP spectrum. In the case of the event of June 19, the GPs controlled the Pc 5 peak near 3.5 mHz on the ELFIM while the RPs controlled peaks near 5 and 7 mHz (Fig. 5).

In the case of the event of September 28, the ELFIM source spectra seemed to be relatively insignificant if the in-phase component (Fig. 2) represents the contribution due to fluctuations in ionospheric attenuation. This interpretation implies that the pulsations in electron precipitation were relatively independent from the ELF waves, or in other words that the CKH mechanism was not producing the precipitation pulsations from interactions between those ELF wave and trapped electrons.

Thus far we have given little attention to GP spectra and the fact that they typically differ significantly from ELFIM spectra, e.g., see the September 28 event. As noted earlier, the observed GPs can, in a specific event, be unrelated to the ELFIM or RP spectra by virtue of being generated on field lines remote from the field line of the site, arriving at the site by cross-field line propagation. Aside fom such spatial considerations, there is the possibility that part or all of the observed GP spectrum is due to type Pi waves

3.2 *June 19, 1978*

The September 28 event was unique on our records for being a case of ELFIM predominantly shaped by ionospheric attenuation of the ELF. Typically there is evidence of control over the ELFIM by both RP and GP. An event occurring on June 19, 1978, illustrates apparent control by GP at a Pc 5 frequency while RP exert control at several other frequencies.

College $\dot{D}$ and $\dot{H}$ have a spectral peak near 3.5 mHz in common with the ELF traces (Fig. 4). On the riometer trace, there are peaks near 5 and 7 mHz that correspond to peaks on the ELFIM traces.

The Fort Yukon riometer data are used in Fig. 4 because the Caribou Peak riometer was not operating. Spectral peaks on the Fort Yukon riometer trace above ~0.01 Hz are suspect because of superimposed man-made noise at those frequencies.

3.3 *September 29, 1978*

A magnetic storm sudden commencement occurred near 0300 UT on September 29. The Caribou Peak riometer registered an absorption event of ~1.1 db following the SSC, while the ELF intensity registered a sharp increase at the SSC then decayed to near zero (Fig. 5). The power spectra (not shown) disclose no meaningful relation between the GP, RP and ELFIM.

The spike of ELF noise seems to represent the initial portion of an ELF event that commenced with the SSC and was masked away from the ground after the build-up

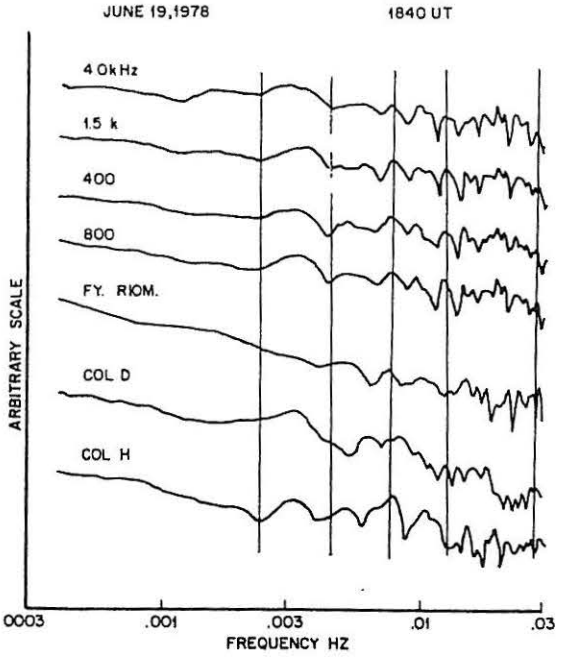


Fig. 4. Power spectral density traces for pulsations occurring on June 19, 1978.

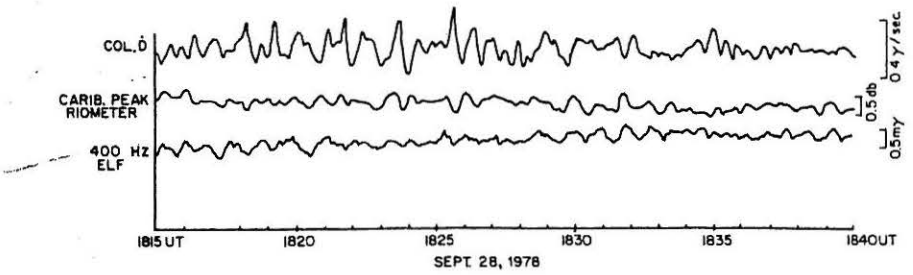


Fig. 2. The riometer and College $\dot{E}$ induction magnetometer traces from Fig. 1 expanded and compared to 400 Hz ELF intensity modulations. ELF intensity increases upwards and riometer absorption increases downwards.

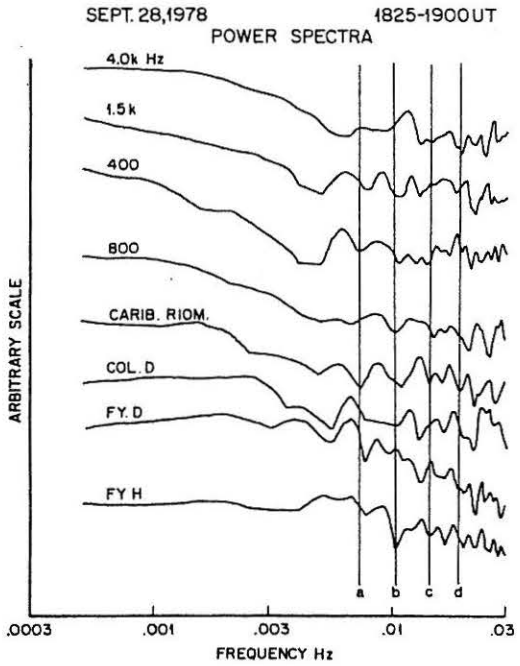


Fig. 3. Power spectral density traces for a portion of the event of September 28, 1978.

For some of the times shown in Fig. 1 and 2, one sees quasi-periodic pulsations. However, the observed periods change through the interval utilized in the power spectra of Fig. 3, i.e., 1825–1900 UT. Thus, Fig. 3 shows a series of peaks rather than a single well-defined peak.

Thus, in this event the ELFIM seem more closely related to RP than to GP, and the phase relations and power spectra also indicate that the ELFIM attenuation spectra dominate the source spectra in this event.

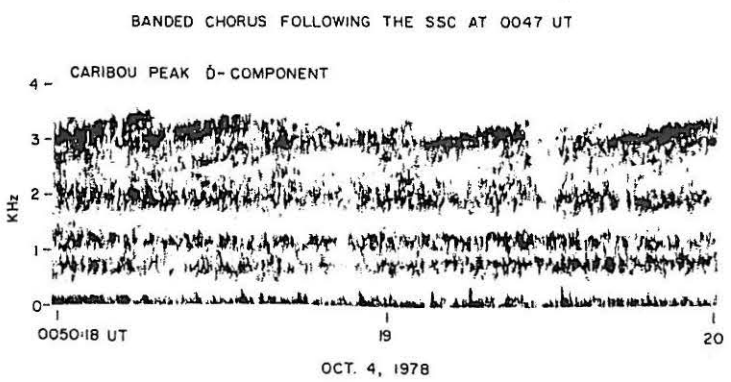


Fig. 7. Showing the character of the ELF activity that followed the SSC at 0047UT, October 4, 1978.

attenuation can significantly affect the ELF spectra seen on the ground.

Figure 7 shows the ELF activity to be of the form called polar chorus with discrete bands rather than the form called high latitude hiss. Chorus is thought to be generated through the electron cyclotron instability.

There are pronounced quasi-sinusoidal pulsations in ELF intensities in the interval 0023–0035 UT. These were accompanied by very weak GPs of nearly the same periodicity (not shown) and by no discernible pulsations in RP. This was the only quasi-sinusoidal event found among several tens of events on ELF intensity records. The typical event had irregular waveform with energy spread over a broad frequency range.

It is of interest that in mostcases among the several tens of ELF events processed, there is high correlation between the envelopes for the different bands, 400, 800, 1,500 and 4,000 Hz, and between the spectral peaks in the power spectra for these four ELFIM bands. Figure 3 is a case where the 4 kHz ELFIM spectra differs from the others, while Fig. 4 shows all four being quite similar.

4. Discussion

This study involved many events for which simultaneous geomagnetic pulsation (GP) and ELF intensity modulation (ELFIM) measurements were taken, and a few events for which precipitation pulsation measurements, in the form of riometer data, were also taken. Of course, in the general case, the observation of GP and ELFIM at a ground site does not imply that the source regions for the GP and ELF were on the field line of the site nor that both wave fields even existed in the equatorial region of that field line. It is well known that ELF-VLF waves may penetrate the ionosphere and then propagate horizontally in the earth-ionosphere waveguide to an observing site, and it is also well established that GP energy may propagate across field lines in hydromagnetic isotropic mode. However, if RPs are simultaneously observed at the site, then the possibility of finding a meaningful relation between the three kinds of pulsations is considerably enhanced.

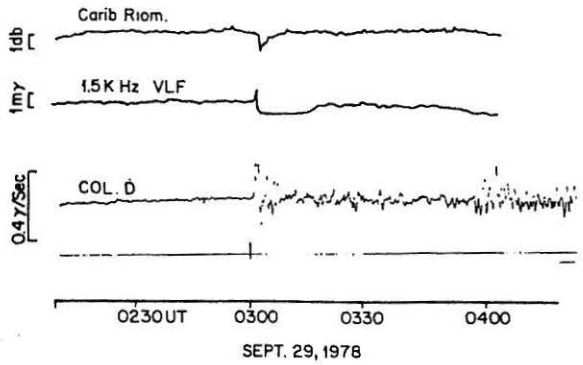


Fig. 5. A magnetic storm sudden commencement occurred at 0300 UT on September 29, 1978, followed by a cosmic noise absorption event. ELF noise appeared at the SSC, then quickly disappeared.

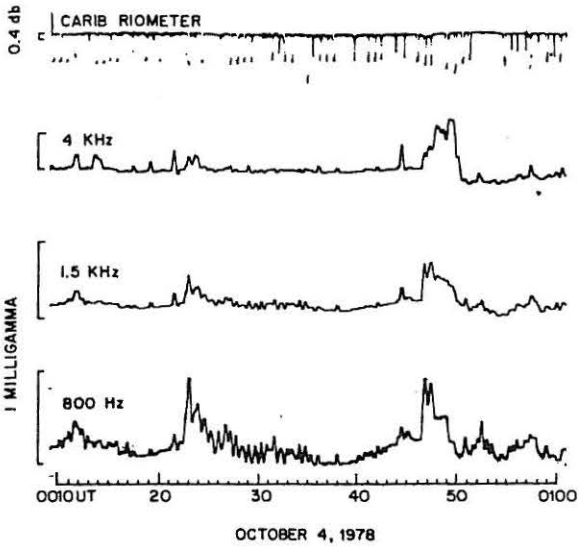


Fig. 6. A magnetic storm sudden commencement occurred at 0047 UT on October 4, 1978, followed by sustained noise. There was no significant riometer absorption. The spikes on the riometer trace are artificial.

ionization in the ionosphere.

3.4. October 4, 1978

This is another SSC event which differs from the above in that ELF intensities increased following the SSC at 0047 UT and did not drop to zero (Figs. 6 and 7). The Caribou Peak riometer registered no significant absorption during this events. These two SSC events are thus consistent with the September 28 event in implying that ionospheric

there.

Magnetic field pulsations were detected by a 3-component induction magnetometer at College (64.6 N, 257.0 E), 35 km south of Poker Flat, and by a 2-component ($\dot{H}$ and $\dot{D}$) flux-gate magnetometer at Fort Yukon (66.8 N, 257.3 E).

The Caribou Peak riometer was operational for only a small percentage of the time that the other equipments were operating, and for most of the time that the riometer was operating satisfactorily, the data were seriously degraded by interference. In the next section, we describe several events for which the riometer pulsation data were of good quality.

3. Data

3.1 September 18, 1978

Figure 1 shows a pulsation event beginning near 1814 UT (0814 LMT) in GP, 800 Hz ELF intensity modulations (ELFIM) and in RP as detected by the Caribou Peak riometer. At this time, College $\dot{H}$ was not operating. The feature of most interest in this event is the good correlation between ELFIM and RP and the fact that the two traces are nearly in phase. These data are shown with expanded time scale in Fig. 2, with 400 Hz ELFIM and riometer trace compared. The same result is obtained, though not shown here, when 800 Hz ELFIM and riometer traces are compared using expanded time scales. In the figure, ELF intensity increases upwards and absorption increases downwards, so that the absorption maxima correspond to ELF intensity minima. The correlation with the College $\dot{D}$ trace is decidedly poorer in each case.

Power spectra of the various quantities are given in Fig. 3. The prominent peaks in RP (riometer) to the left of lines a, b, and c correspond well with peaks on the ELFIM spectra except for the 4 kHz case. The peak-to-peak correspondences between the spectra for GP and RP are considerably poorer.

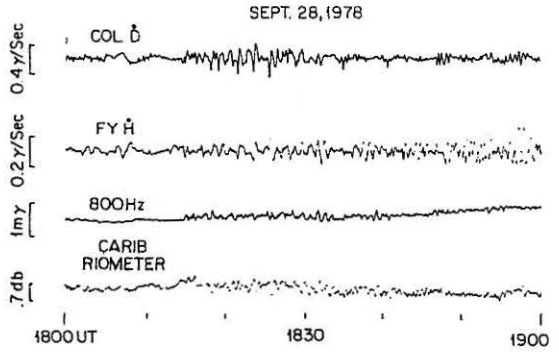


Fig. 1. Example of pulsations occurring simultaneously in the geomagnetic field, in ELF intensity (800 Hz band shown) and in electron precipitation as detected by the 30 mHz riometer. The pulsation amplitudes, in all cases, increase near 1814 UT (00814 LMT) which was the onset time of a substorm.

[illegible] waves (GPs) modulated the growth rate of VLF emissions which are generated through the electron cyclotron instability. SATO and KOKUBUN (1980) presented conjugate-site evidence that whistler mode turbulence interacts with Pc 3–4 waves in the equatorial region, and they noted that this evidence is consistent with theories such as CKH.

An important consequence of these interactions is the pulsating precipitations of electrons into the ionosphere; this is the phenomenon that the CKH theory aims to explain. Obviously it would be desirable to have precipitation pulsation data along with both ELF-VLF and GP data, but it seems that this was rarely if ever accomplished in ground-based recording programs. All three quantities were measured simultaneously in a rocket experiment (GENDRIN *et al.*, 1970). It is of interest to note that riometer (cosmic noise absorption) data have been used to determine occurrences of long period ($T>2$ min) precipitation pulsations, and collections of such riometer pulsation (RP) events with concurrent GPs of the same periodicity have been reported and studied (BARCUS and ROSENBERG, 1965; PARTHASARATHY and HESSLER, 1964). More recently, concurrent GPs and RPs of shorter periods were reported and studied (REID, 1976; HEACOCK and HUNSUCKER, 1977). The possibility of extending the studies cited above and of testing the CKH theory led us to a study of ELF-VLF, GP, and RPs recorded simultaneously in Alaska.

One complication in interpreting ELF-VLF data recorded on the ground comes from the possibility that the ionospheric attenuation coefficient for ELV-VLF fluctuates with time and thereby introduces a significant intensity modulation onto the ELF-VLF as seen on the ground. The time-varying power spectra of the ELF intensity modulations (ELFIM) for ELF waves incident on the top of the ionosphere may be called the source spectra, and the modification due to the ionosphere called the attenuation spectra; the spectrum observed below the ionosphere is the product of the source and attenuation spectra. In many of the studies of apparent modulations of ELF-VLF by GPs, it was tacitly assumed that the ELFIM spectra recorded on the ground corresponded to source spectra, i.e., the attenuation effect was assumed to be insignificant. In the present paper, we show that in some events at least, the attenuation spectrum is a significant factor.

2. Equipment

ELF-VLF emissions in the range 15 Hz to 4.5 kHz were detected with a 3-component ($\dot{H}$, $\dot{D}$, $\dot{Z}$) loop antenna receiver system on Caribou Peak in Alaska (65 N, 257.1 E, GM). We shall hereafter refer to this range as ELF, though it overlaps with part of the standard VLF range. The site was unmanned and the data were telemetered to Poker Flat Research Range 10 km south of Caribou Peak, for recording. The ELF signals were recorded routinely on magnetic tape in direct mode on a 1 : 15 sampling schedule, i.e., the recorder operated for 1 min every 15 min. Additionally, the D-component data were filtered into four bands centered on 400, 800, 1,500, and 4,000 Hz, and the envelope of each band was detected and recorded in frequency-modulation mode on magnetic tape.

The Caribou Peak equipment included a fast-response 30 MHz riometer with a

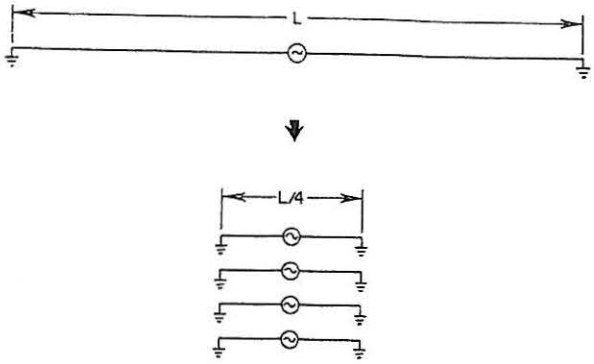


Fig. 6. The equivalence at ELF between a single grounded wire radiator and a parallel array.

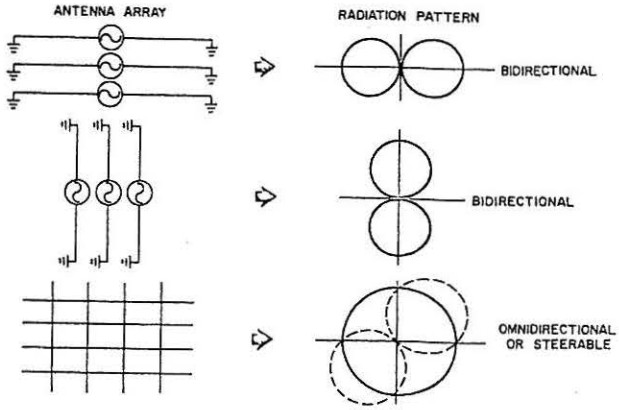


Fig. 7. Basic antenna radiation patterns in horizontal plane.

BASICS OF ELF PROPAGATION

Now that we have constructed and installed our antenna grid, we should indicate how the energy is launched. The concept is illustrated in Fig. 8 that was adapted from a U.S. Navy news release. As suggested, the signal emanates from the land-based antenna and propagates through the atmosphere above the sea surface. The ionosphere, as we shall discuss later, acts as the upper "boundary" of a waveguide; the lower boundary is the sea. The electric field lines are predominantly vertical, but the finite conductivity of the sea requires that there be a relatively small horizontal component. It is this component that launches a downward propagating wave to the submerging receiving antenna. Because of the large conductivity of the sea, the electric field in the ocean is predominantly horizontal while the signal amplitude is attenuated exponentially with depth. It goes without saying that the directly propagated signal, from the coast line, through the sea water to the submarine is of no consequence. The total attenuation of such a signal would be enormous.

We now wish to consider the nature of the relevant propagation phenomenon in more detail. To this end we illustrate a portion of the earth–ionosphere waveguide in Fig. 9(a). The source is depicted as a horizontal wire antenna of length l grounded at end point and energized by an ac generator. The effective height of the waveguide is h_i. At some distant point, the electric field vector E has both a horizontal component E_H and a relatively large vertical

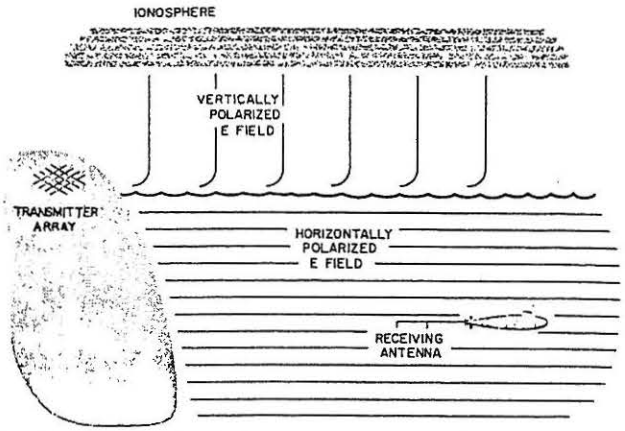


Fig. 8. The Sanguine/Seafarer system as envisaged by the U.S. Navy.

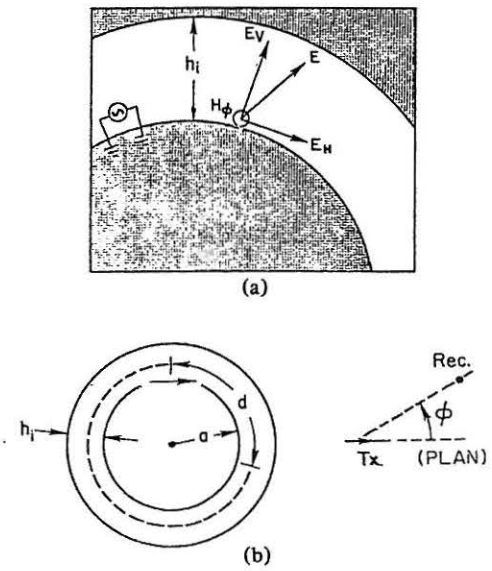


Fig. 9. (a) A portion of the earth–ionosphere waveguide in the vertical plane containing the equivalent single wire radiator. (b) The full earth–ionosphere cavity excited by the horizontal wire source.

component E_V. On the other hand, the associated magnetic field has only an azimuthal component H_ϕ. At least this would be the situation if the ionosphere were acting as an isotropic conductor. As it turns out, this is a reasonable first-order approximation.

A useful working formula for the vertical electrical field strength $|E_V|$ a great circular distance d from the transmitter over a spherical earth of radius a is given approximately by [17], [18]

$$|E_V| \cong \text{const} \times f \cdot Il \frac{1}{h_i \sigma_{\text{eff}}^{1/2}} \cdot \frac{1}{[a \sin (d/a)]^{1/2}} \cdot e^{-\alpha d} \cdot \cos \phi. \quad (1)$$

This corresponds to the field in the dominant zero-order mode. The symbols are defined as follows.

f is the operating frequency.

Il is the moment or current-length product of the transmitting antenna.

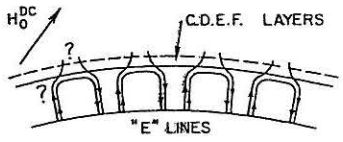


Fig. 10. The electric field lines in the dominant ELF mode of propagation in the earth–ionosphere waveguide.

$1/h_i\sigma_{\text{eff}}^{1/2}$ is an excitation factor being inversely proportional to the ionosphere height and the square root of the effective ground conductivity σ_{eff} at the transmitter site.

$1/[a \sin d/a]^{1/2}$ is a factor that behaves as $1/d^{1/2}$ for a flat earth but exceeds $1/d^{1/2}$ for a spherical earth by the ratio $d/a)/\sin (d/a)]^{1/2}$. (This factor is not valid at or near the antipode of the transmitter.)

$e^{-\alpha d}$ accounts for the leakage out of the earth–ionosphere waveguide due to losses in the upper and lower boundaries; here α is the attenuation rate in nepers per unit distance.

$\cos \phi$ is the radiation pattern factor in terms of the angle ϕ measured from the direction of the antenna.

As indicated in Fig. 9(b), the signal can actually propagate to the receiver via the direct great circle path and via the antipodal path. We neglect the latter signal here but we should bear in mind it may be of equal importance if the receiver is in the antipodal region.

THE IONOSPHERE BOUNDARY

The transmission properties of the earth–ionosphere waveguide depend in a rather complicated manner on the electron and ion constitutents of the ionosphere. To understand this dependence, we illustrate in Fig. 10 the configuration of the electric field lines at some frozen point in time in a region of the earth–ionosphere waveguide. The field lines are almost vertical at the bottom boundary but they terminate in the ionosphere in a rather complicated manner. In fact, the conventionally designated *C, D, E,* and *F* layers may all play a role as we have suggested in Fig. 10. Furthermore, the direction and strength of the earth's magnetic field denoted H_0^{DC} will modify the transmission characteristics of the waveguide channel.

The various mathematical theories that have been worked out for this problem show that the mode equation for the earth–ionosphere waveguide can be written in the form [19], [20]

$$({}_{\parallel}R_{\parallel}\, e^{-2ikhC} - 1)({}_{\perp}R_{\perp}\, e^{-2ikhC} + 1) - {}_{\perp}R_{\parallel} \cdot {}_{\parallel}R_{\perp}\, e^{-4ikhC} = 0 \qquad (2)$$

where $k = 2\pi/\text{wavelength}$ and where the R's are reflection coefficients for the ionospheric boundary at the reference height h, the C of which is the cosine of a complex angle θ. To be more specific, ${}_{\parallel}R_{\parallel}$ is the reflection coefficient for a vertically polarized plane wave incidence at an angle θ, ${}_{\perp}R_{\perp}$ is the corresponding reflection coefficient for a horizontally polarized plane wave, while ${}_{\perp}R_{\parallel}$ and ${}_{\parallel}R_{\perp}$ are reflection conversion coefficients that account for the depolarization of the fields reflected from the ionosphere. Equation (2) must

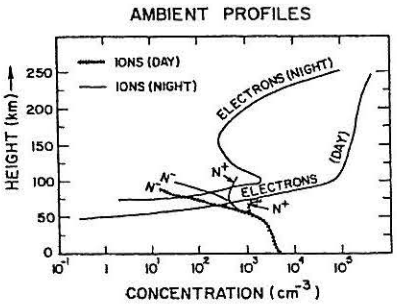


Fig. 11. The upper boundary of the waveguide.

actually be solved for the eigenvalues C_0, C_1, C_2, etc. The attenuation rate and phase velocities of the modes are then obtained from the corresponding sines S_0, S_1, S_2, etc. In particular, for the zero-order mode, the attenuation rate is calculated from

$$\alpha = -\text{Im} \cdot kS_0 \text{ Np/m}$$

where Im denotes that the imaginary part be taken. At ELF, the attenuation rate of the higher order modes is so high that they can be ignored for any distances d greater than 300 or 400 km.

To determine that matrix reflection coefficient

$$\begin{bmatrix} {}_{\parallel}R_{\parallel} & {}_{\perp}R_{\parallel} \\ {}_{\parallel}R_{\perp} & {}_{\perp}R_{\perp} \end{bmatrix}$$

in terms of the physical constitutents of the ionospheric plasma, we must solve Maxwell's equations for such an anisotropic medium. Many such calculations have been made for ambient day and night ionosphere models such as those sketched in Fig. 11. The concentration of the electrons and the ions, in terms of particles per cubic centimeter, are plotted as a function of altitude in kilometers. Both typical day and night profiles are shown. The data for the region from the ground to 100 km are from Knapp [21] and those above 100 km are from Johnson [22]. The collision frequencies, which are a measure of the collision between the charged and neutral particles, must also be known. Fortunately, these are quite well behaved and they have an exponentiallike decrease with height. The ambient profiles indicated in Fig. 11 should be regarded as representative of undisturbed conditions [22] and they should not be regarded otherwise.

Once we know the expected form of the electron and ion density profiles, we may use classical magnetoionic theory [23] to deduce the effective conductivity of the ionosphere for the desired frequency. This conductivity is actually a matrix but the important elements are the parallel conductivity $\sigma_{\parallel}$, the Petersen conductivity σ_p, and the Hall conductivity σ_h. For an ambient daytime condition, the general forms of the height variation of these quantities for ELF are shown in Fig. 12 for heights up to 200 km. The region tends to be isotropic in the lowest atmosphere and the conductivity σ_A just above the earth's surface is of that order of 10^{-13} mho/m. Variations of this quantity, due to pollutants, can be as much

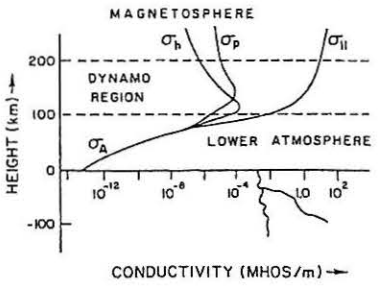


Fig. 12. The conductivity structure of the atmosphere at ELF.

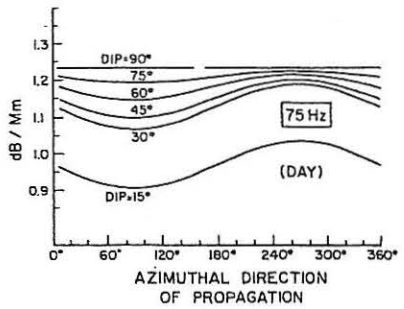


Fig. 13. Calculated daytime attenuation rate over sea water (after Pappert and Moler, 1974).

as a factor of 100. In the region beneath the earth's surface over land, the conductivity is of the order of 10^{-2} mho/m, but again wide variations can be expected. On the other hand, for sea water σ_e would be around 4 mho/m with variations by a factor or 2 or 3 in different parts of the globe.

ELF WAVE CHARACTERISTICS

Using model data of the type described previously, Pappert and Moler [24] have made what is considered to be the most sophisticated set of calculations of the expected attenuation rate of the dominant zero-order mode. They use a full wave theory that takes account of the earth's curvature and the presence of the earth's magnetic field. Typical calculated results of the attenuation rate in decibels per megameter as a function of the azimuthal direction of propagation are shown in Figs. 13 and 14. The azimuthal direction of 0° corresponds to propagation towards the north in geomagnetic coordinates while 90° would correspond to propagation towards the east. In general, we see that for a propagation at the magnetic poles (i.e., magnetic dip angle is zero), the attenuation rate does not depend on the azimuthal direction of propagation. But of most interest is the fact that the propagation towards the east has a lower attenuation than for propagation towards the west. This nonreciprocity in transmission is more pronounced at night than in daytime this is an effect that has been studied extensively in the VLF band (i.e., frequencies from 10 to 30 kHz) [19]. The phase velocity of the mode is also a function of the azimuthal direction of propagation except at the poles [20].

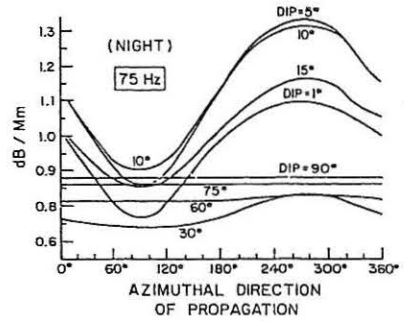


Fig. 14. Calculated nighttime attenuation rate over sea water (after Pappert and Moler, 1974).

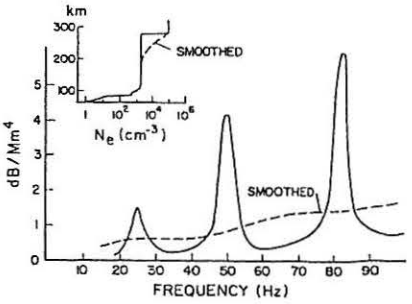


Fig. 15. Intralayer profile resonance effects.

Not surprisingly, the attenuation rate will depend in a major way on the nature of the profile of the charged particles as a function of altitude. An example of what can be expected is illustrated in Fig. 15 where the electron density profile is shown that has an abrupt increase at 300 km along with a smoothed version. The attenuation rate, for the profile with a sharp gradient, as a function of frequency, shows a series of pronounced maxima due to intralayer resonance effects. However, the resonance peaks almost disappear completely in the case when the profile is smoothed.

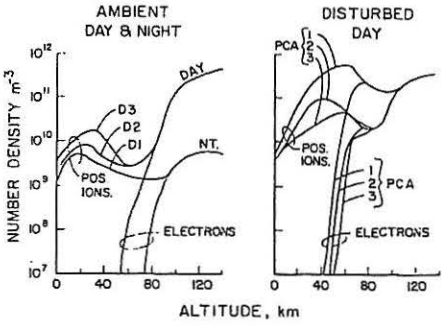


Fig. 16. Ionization height profiles (after E. C. Field, 1969).

An important analysis was carried out by Field [25] to predict the dependence of ELF propagation upon various ionosphere properties in the frequency range 30–1000 Hz. The various ionosphere models used in the analysis include both electron and ion concentrations. The ionization profiles for both undisturbed and disturbed conditions are illustrated in Fig. 16. The models of the undisturbed or ambient profiles were chosen mainly to illustrate the sensitivity of the computed ELF model characteristics to the ion profile used. The three daytime models (D1-D3) utilize the same electron concentration but different ion profiles. The electron profile is considered to be typical [26] while the profiles D1-D3 span those in

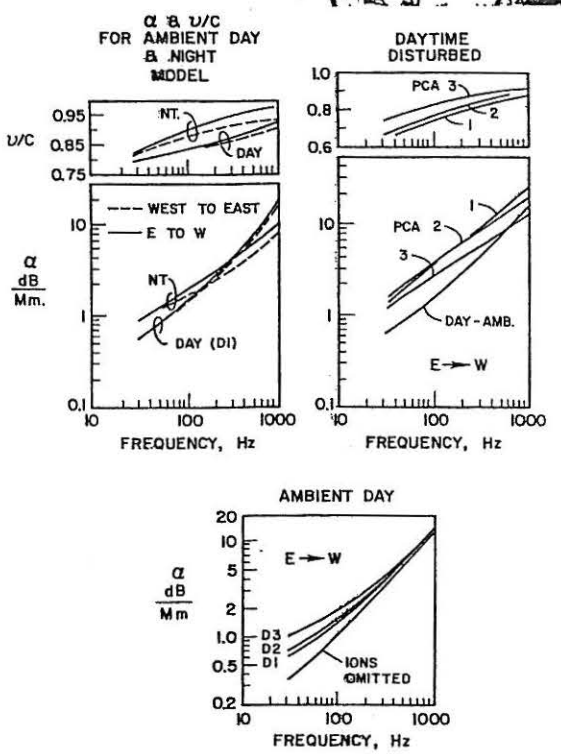


Fig. 17. Attenuation calculations for profiles in Fig. 16.

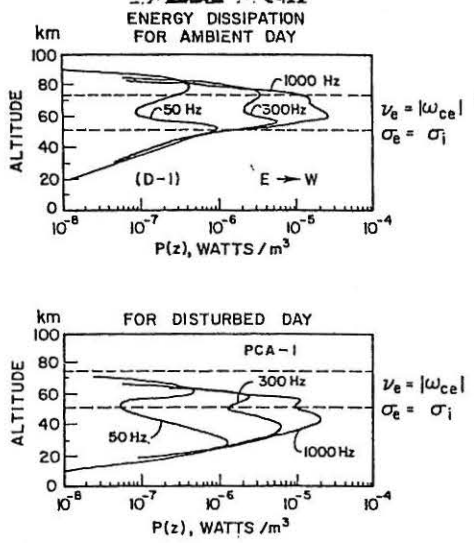


Fig. 18. The dissipation of energy in the atmosphere as calculated by E. C. Field (1969).

rrent use [27]. The high-density D3 model represents high itudes. The one nighttime model, denoted NT, corresponds fairly low latitudes.

Following Field [25], we also show in Fig. 16 three daytime ıization models that result from a polar cap absorption CA) event of various intensities. These PCA models are rived from actual measured incident fluxes of solar protons ch as discussed by Field [25] and by Adams and Masley 8]. The PCA-1 model corresponds to a relatively strong ent while PCA-2 and PCA-3 are more typical. There is a eat deal of uncertainty in such calculations, but it is safe to y that ELF propagation is governed largely by the ionic ntributions during PCA events. For this reason, the major rors inherent in the electron density profiles are not too ;nificant.

The attenutation rate α and the phase velocity v (relative to e speed of light c), are shown in Fig. 17 for the profile odels for Fig. 16. In spite of the complexity of the various ofiles, the curves of α and v/c as a function of frequency are markably smooth. The attenuation rate is always a monoton- ılly increasing function of frequency over the range from 10 1000 Hz. Also we note that there is some nonreciprocity hen comparing the attenuation rate for propagation direction om west-to-east with those for east-to-west. But the most ıportant observation is that the attenuation rate is increased ;nificantly during disturbed conditions.

Some extremely interesting calculations have been carried ıt by Field [25] for the Joule heat or power dissipated ithin the ionosphere. Some examples of such calculations are

1 V/m where $\eta_0 = 120\pi\ \Omega$. As a guide to interpretation, we show the altitude where ionic conductivity σ_i equals the electron conductivity σ_e and the altitude where the electron collision frequency ν_e equals the magnitude of the electron gyro frequency ω_{ce}. The quantity $P(z)$ actually plotted in Fig. 18 is defined by

$$P(z) = 1/2\ \mathrm{Re}\ E^* \cdot J \ \mathrm{in\ W/m^2}$$

where E^* is the conjugate of the vector electric field and J is the resultant current density at the height z above the earth's surface. These results show much of the power dissipation takes place over a restricted range of altitudes. However, during the disturbed PCA condition, the lower altitudes are more important. In fact, under such PCA conditions ions are really controlling the propagation. Furthermore, in such situations the geomagnetic field has a negligible effect.

THE SCHUMANN CAVITY RESONANCES

As indicated earlier, the observer actually receives two important signal contributions. One of these corresponds to the direct propagation along the shortest great circle path, while the other is a delayed signal that travels via the longer great circle path. Both contributions may be of comparable importance in many practical situations. In fact, at frequencies of the order of 10 Hz, we can visualize that the two signals may constructively interfere to produce an apparent resonance of the earth–ionosphere cavity. In such cases, the circumference of the earth is comparable with the propagating wavelength. On this basis, we would also expect to have resonance effects at higher harmonics and indeed this is the case. The original idea that the earth can be resonated could be traced back to the prophetic notions of Tesla. However, his concept of the energy flow was hardly tenable even in his day. The first

) factors yield information concerning the attenuation rate of he ELF propagation mode.

SANGUINE PROPAGATION TESTS

Some important propagation measurements of man-made ELF signals were made in late 1966 by Ginsberg [36] and his associates at RCA, from a Sanguine-type antenna in North Carolina with receiving sites in New York State, Labrador, and celand. The attenuation rate α in decibels per megameters and he excitation factors were determined from the observed data. Some examples of Ginsberg's data, for 78 Hz, are shown in Fig. 21 where the "night" and "day" conditions refer to 3-h ime blocks where the paths were entirely dark or entirely lit, respectively. The straight lines that are least square fit to the lata are indicated in Fig. 21. The error bars in this figure ndicate the deviations of the field strength for each of the ocations. The deduced mean attenuation rates of 1.01 and 1.29 dB/Mm for night and day, respectively, are not inconsistent with other experimental results using natural signals. More will be said about this below.

A very extensive and ambitious program was later carried out by White and Willim [37] and their colleagues at the Lincoln Laboratory to determine ELF propagation parameters using a Sanguine facility in Wisconsin. The radiated power was of the order of 0.5 W at 45 Hz and 1 W at 75 Hz. Receiving sites were located in Nova Scotia, California, Utah, Hawaii, Norway, Greenland, Greece, and Saipan. The configuration of the great circle paths from the Wisconsin test facility transmitter to some of the indicated receiver sites is shown in Fig. 22 where the distances indicated are expressed in megameters. As indicated in the caption to this figure, the attenuation rates are of the same order as found by Ginsberg [36]. It should be stressed that such derived propagation data refer to values averaged over many minutes of actual observations. To obtain data on short-term variations, much higher transmitter powers would be needed.

Some very careful and important measurements on the structure of the Wisconsin test facility antenna pattern have been made by Bannister *et al.* [38]. They found some interesting distortions of the pattern that could be attributed to local nonuniformities in the effective ground conductivity at the site.

SUMMARY OF ELF ATTENUATION

At the risk of great oversimplification, experimental data on ELF attenuation from many sources are summarized in Fig. 23 over a range from roughly 7 to 1000 Hz. The indicated RCA data are described in Ginsberg's paper [36] that was already cited. The MIT data points are from the results described by White and Willim [37]. For the region below about 100 Hz, the data from the resonance frequencies and Q factors from the earth-ionosphere cavity measurement are indicated as Schumann resonances in Fig. 23. The remaining solid curves are based on data derived from the frequency analysis of radio atmospherics. The early work of Chapman and Macario [39] employed only one receiving station, and

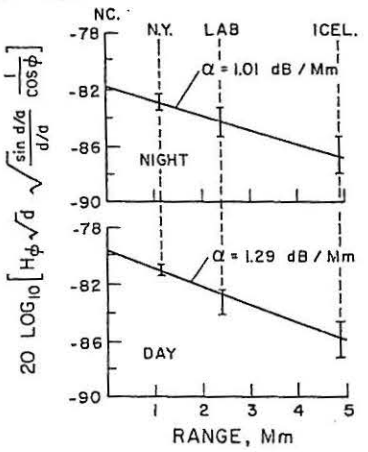


Fig. 21. Least squares fit of observed 78-Hz propagation data (after Ginsberg, 1974).

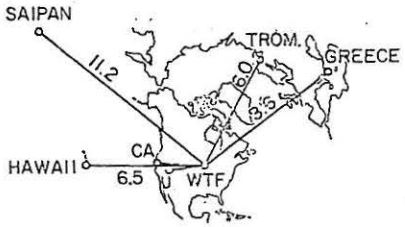


Fig. 22. Receiver site locations for Lincoln Laboratory experiments

at 75 Hz	α_{day}	1.2 dB/Mm	1.0 dB/Mm
	α_{night}	0.8 dB/Mm	1.0 dB/Mm
at 45 Hz	α_{day}	1.5 dB/Mm	1.4 dB/Mm
	α_{night}	0.9dB/Mm	1.3 dB/Mm.

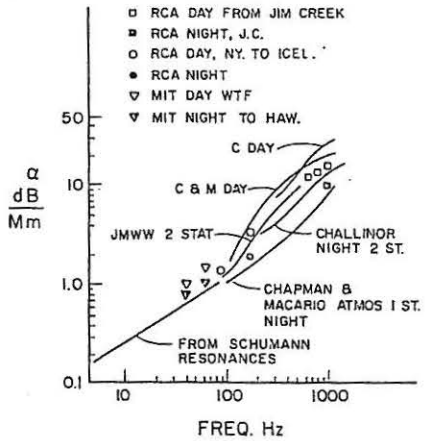


Fig. 23. ELF attenuation rates from various sources.

they were required to assume a reasonable frequency spectrum for the causative lightning stroke. Later, such techniques were extended by Challinor [40] to simultaneous waveform recording of individual events at spaced stations. In this manner, the source spectrum need not be assumed. Some data of this type for very long propagation paths were obtained by Jean *et al.* [41], and they are designated as JMWW in Fig. 23.

Guide to Papers in This Issue

JAMES R. WAIT, *Guest Editor*

FOR THE CONVENIENCE of the readers, I will attempt to give an overall summary of the salient points from each of the papers. They are discussed in the same order that they are listed in the Table of Contents.

GENERAL CONSIDERATIONS

Merrill describes the Navy's need for a secure transmission capability to submerged FBM submarines. He points out that in April 1963, the Navy conducted a communication demonstration between a shore-based ELF (30–300 Hz) radio transmitter located in N. C. and a nuclear submarine operating at a range of 3200 km with its receiving antenna near keel depth. Termed the "Intensive Test," this event established the fact that a deployed submarine could receive messages from the continental United States without its receiving antenna being on or near the surface of the ocean and without severe reductions in the submarine's operational capability during reception. This was a most important "first" in the history of submarine communications.

Keiser describes the early research on ELF radiating systems at R.C.A.: the recognition of equivalences among several of the candidate systems; the conduct of an early transmission experiment; and the initial efforts at system optimization and choice of the radiating system configuration. These early investigations provided confirmation of the theory that a vertically polarized E-field propagates through the earth–ionosphere cavity at ELF with a slight forward tilt which allows it to enter the sea water and then penetrate to considerable depths.

Rowe makes a self-contained and objective study of an ELF (extremely low frequency) communication system for communication from land to submerged submarines (i.e. Project Sanguine). He presents an analysis of the conceptual feasibility of such a system. He concludes that there is no fundamental technical reason why such a system is infeasible. He emphasizes that nonlinear processing ahead of the FSK (frequency shift keying) receiver in the submarine appears essential. Such processing greatly reduces the effects of atmospheric noise due to nearby lightning storms, and hence, makes reliable operation possible at much smaller transmitter power. This point is discussed in later papers.

In a companion paper, Chu uses a well known heuristic approach to show how ELF waves are radiated from a horizontal electric dipole. While this image method and the theoretical developments are available elsewhere, this paper serves as good introduction to the propagation phenomenology. The interested reader may wish to compare this development with a significant study by Dr. H. G. Booker.[1] He deals with the physics of the radiation into the earth-ionosphere waveguide from a long horizontal wire grounded at its two ends. Booker presents compelling arguments to show that the earlier estimates by McLintock *et al.* and calculations by Johler and Lewis are wrong! The latter lead to very pessimistic performance predictions that are not borne out by experience.

SITE SELECTION AND ANTENNA DESIGN PROBLEMS

Davidson, Macklin, and Vozoff demonstrate the application of certain dc resistivity sounding methods in rapidly evaluating potentially useful for Sanguine type transmitters. Apparent resistivity data from dc measurements are interpreted using horizontal layered earth models.

Sainati and Wolkoff show that the magnetotelluric resistivity method can be used to assess a proposed Sanguine transmitter site and to predict the radiation pattern of the transmitting antenna. The magnetotelluric resistivity method, unlike other conductivity measuring techniques, can account for the anisotropic behavior of the earth, and measurements can be obtained rapidly as compared with other techniques.

Burrows points out that the effective conductivity of a potential antenna site is a measure of the field strength that an antenna built on the site would radiate. Only in special cases, however, is this same measure suitable for characterizing the power that the antenna would dissipate. He shows that, in the case of a current sheet antenna built on a horizontally stratified half-space, a measure that characterizes both the radiation and dissipation properties of the site is the complex surface impedance. This same measure remains substantially valid for an antenna composed of separate cables and for inhomogeneous half-spaces of not too great lateral variation. He concludes that the most reliable methods of measuring the surface impedance are the E/H and H/I techniques provided phase is also measured. Burrows, in a second paper, uses the surface impedance concept to examine the effect of ground anisotropy on the radiated field and power dissipation of a horizontal ELF transmitting array. This has relevance to the skewing of the antenna pattern. Burrows then considers the impedance, effective length, and current distribution of grounding electrodes that are needed for terminating a Sanguine transmitting antenna. He shows that little is to be gained in making the electrode

[1] H. G. Booker, "The ionosphere as the secondary conductor of a transformer for ELF," *Radio Science*, vol. 8, no. 8–9, pp. 757–762, Sept. 1973.

longer than a skin depth, unless the current distribution can be forced to spread out further along the electrode. In a following paper, he determines the current distribution in a buried linear antenna that minimizes the dissipated power while maintaining the required radiated field. He shows that such a distribution saves about 30 percent on power dissipation compared to an antenna of the same total length having simple bared-end grounding terminations.

Bannister *et al.* describe pattern and steering measurements on the Wisconsin Test Facility antennas. The pattern measurements were made at 13 locations in Minn. and Wis. (covering approximately 120° of arc), while the far-field steering tests were taken in Me. and N. C. The 45 Hz and 75 Hz pattern measurements were made at a range of approximately 300 km, while the steering measurements were performed at 1.7 Mm. The principal results from the pattern and steering measurements were that the east–west antenna pattern was skewed clockwise, while the north–south antenna pattern was skewed counterclockwise; also they deduced that the effective conductivity under the east–west antenna was greater than the effective conductivity under the north–south antenna. In the following paper, Bannister and other coauthors describe the relative performance of buried and elevated ELF transmitting antennas in Wis. They conclude that there is no significant difference for their configurations.

Chang and Wait determine the propagation constant of a long horizontal thin-wire that is located above, on, or beneath the earth's surface. This study shows that a horizontal antenna could behave in much the same manner whether it is elevated or located in a buried cylindrical insulating cavity. This presupposes, of course, that adequate grounding of the end points is achieved.

Fessenden and Cheng review submarine trailing-wire receiving antenna developments during the past 15 years that relate to Project Sanguine. Although the models have been tested extensively during numerous sea trials, unanswered questions, concerning the impedance theory of the submerged bare conductor as an electrode element, remain.

PROPAGATION PHENOMENA

Pappert and Moler outline a general theory of the propagation of ELF waves in the earth–ionosphere waveguide. Their calculations for a diffuse anisotropic ionosphere model are considered to be the most sophisticated and reliable of many such attempts to predict field strengths at megameter ranges.

Ginsberg describes some significant experiments concerning ELF electromagnetic wave propagation to large distances. He and his colleagues measured the amplitude of a CW signal transmitted from the Sanguine site in N. C. to receiving sites located in New York State, Labrador, and Iceland. The attenuation factor and the excitation factor were determined for daytime, nighttime, and during sunrise transitions. Attenuation values of 1.3 at 78 Hz and 1.0 dB/1000 at 45 Hz, were deduced.

White and Willim have conducted an experimental measurement program to determine propagation parameters in the 40–50 and 70–80 Hz range. Their measurements utilized a transmitter in Wis. radiating a sinusoidal signal at radiated power levels of 0.5 W at 45 Hz and 1 W at 75 Hz. Sites were located at Nova Scotia, Calif., Utah, Hawaii, Norway, Greenland, Greece, and Saipan. Using sites on the same great circle path as the transmitter, it was possible to estimate *average* attenuation rates and excitation factors with high accuracy. Bannister, in the following paper, describes similar ELF propagation tests. His receiving sites were located in Conn., N. C., Me., Utah, Nova Scota, Calif., Greenland, the Virgin Islands, Alaska, Norway, Hawaii, Greece, and Saipan. At each location, the horizontal magnetic field strengths were measured at a band of frequencies centered at 45 Hz and 75 Hz in order to determine the average attenuation rates and relative excitation factors for daytime and nighttime propagation conditions. The Wisconsin Test Facility was the transmission source. The principal results obtained from these measurements were: 1) the daytime attenuation rate is usually higher than the nighttime attenuation rate at both 45 and 75 Hz; 2) the relative excitation factors are quite different for daytime and nighttime propagation conditions; 3) nighttime propagation is more variable than daytime propagation; 4) there is a seasonal variation in the ELF propagation parameters; and 5) auroral-zone effects appear to be present at both frequencies. Bannister and his colleagues have also demonstrated that there are substantial variations in the ELF nighttime propagation parameters. On a few occasions, the nighttime field strength was approximately 2–5 dB lower than on preceding or proceeding nights. This nighttime field strength reduction has been observed at various frequencies and at other measurement locations. It appears to be due mainly to a decrease in the nighttime excitation factor, rather than to an increase in the nighttime attenuation rate. There also appears to be a correlation between ionospheric irregularities and these lower than normal nighttime field strengths.

Jones discusses methods for obtaining propagation parameters—attenuation and phase velocity, of subionospherically propagated radio waves using lightning sources. Attention is confined to the ELF band which encompasses the region 3 Hz–3 kHz. He points out that there are available two rather different techniques. Firstly, in the band 5–50 Hz, observations of the resonances of the earth–ionosphere spherical shell (Schumann resonances) and of circumglobar signals may be made. Secondly, in the range 50 Hz–2 kHz, "slow tail" atmospherics enable the determination of propagation path parameters. In both cases the electromagnetic radiation characteristics of the source are variable and generally unknown. This primary difficulty of the use of natural sources can be overcome in a number of ways. A technique which is becoming important is that of observing the wave impedance of the signals rather than acquiring data on only the electric or

Davis suggests that a number of phenomena may cause irregularities in ELF ionospheric propagation. Some examples are: geomagnetic anisotropy, path asymmetry due to different ionospheric characteristics on the darkened and sunlit hemispheres, effects of strong boundary discontinuities such as the twilight zone or northern latitude sporadic E, and the effects of geophysical trauma such as solar particle fluxes. His analysis of the ELF propagation data indicates that an association can be drawn between the effects of solar charged particle emissions and coincident ELF propagation irregularities. Paths that pass through the auroral zone appear to be most severely affected.

Ghose has designed and implemented an ingenious physical model to simulate the earth–ionosphere space appropriate for ELF wave scaled propagation path (up to 20 000 kilometers) and for a frequency range of 35–55 Hz. Measured data on the ELF propagation in the form of amplitude and phase variations of a signal along the propagation path for various simulated ionospheric reflection heights are also given.

SIGNAL PROCESSING AND THE NOISE ENVIRONMENT

Mullen points out that an ELF communication system for naval purposes needs specialized engineering techniques, particularly signal bandwidth spreading in order to protect against enemy ECM. He describes the processing that the system must have to make jamming difficult. He also discusses predictive jamming, repeat back jamming, and high power brute force jamming by adapting electric power systems.

White computes the degradation in correlation receiver performance due to signal distortion at the transmitting antenna as a function of processing delay for simple but representative models of the Sanguine antenna and input waveforms. The optimum delay and minimum distortion loss are given parametrically in terms of the ratio of the 3-dB bandwidth of the signal process to that of the antenna. He claims that, for the more realistic model considered, the degradation can be reduced to just a fraction of a decibel by optimizing the receiver delay.

Bernstein, McNeill, and Richer point out the efficient signaling schemes and sophisticated receiver designs help minimize the required transmitter power and hence, system cost. One such signaling scheme is convolutional encoding and binary antipodal modulation; they tested an experimental receiver aboard a submerged submarine in the Atlantic Ocean. They utilized adaptive nonlinear noise processing, notch filtering, ocean channel compensation, and sequential decoding. These are all factors that make extremely efficient usage of available signal strength and conclusively demonstrate the technical feasibility of communication in the ELF band.

Evans and Griffiths describe the design of a noise processor for the Sanguine receiver based on communication theory considerations and detailed experiments using wideband recordings of ELF (3–300 Hz) atmospheric noise. The processor consists of the following elements: a compensating (or whitening) filter, nonlinear notch filtering at frequencies of manmade interference, a post-notch filter nonlinearity, and a phase coherent linear match filter. Due to the impulsive non-Gaussian nature of the noise, nonlinear processing with a bandwidth considerably greater than the 40–80 Hz signal bandwidth is significantly better than a linear receiver. Simulations using noise recordings from a number of widely separated locations in the world have shown improvements of 7 dB to over 20 dB at times of high ELF atmospheric noise levels at the receiver input.

Burrows points out that the pressure fluctuations in the turbulent boundary layer surrounding the towed receiving antenna cable cause it to vibrate in the geomagnetic field and thereby generate noise. This noise mechanism is proposed as the dominant one in currently used long antennas. Its effect can be reduced only by increasing antenna diameter and length. Tension, stiffness, and damping have no effect. Noise voltage spectra derived from pressure fluctuation data show striking agreement with those measured. Cafaro, Dalsass, and O'Brien, in a related study on stress induced core noise, show that a substantial improvement signal to noise ratio is realized by cold-working the antenna core into a helically wrapped or solenoidal structure. The advantage of a helical core design over an axial design is shown to be due to the mechanical strain relief, or insensitivity to tensional stresses, of the helical structure. Then Wolf, Davis, and Nisenoff believe that the ferromagnetic-core type of solenoid that is used as a towed antenna for communications reception by submarines is not adequately sensitive to satisfy the performance requirements for deeply submerged submarines receiving ELF transmissions from the planned Sanguine communications system. They propose that a superconducting quantum interference device can be adapted to this role and they present some laboratory measurements that prove the potential of these devices for the ELF communications reception capability.

Ginsberg describes the statistics of narrow band ELF noise obtained at locations in Malta and Guam. He presents the results of four seasons of ELF atmospheric noise measurements. Spectra of the 1-percent and 50-percent exceedance levels of the magnetic field intensity component, obtained from the sensor aligned for maximum reception from northern Wis., are given. At both locations, the noise levels were found to be highest during the fall season. The diurnal variation of the median noise levels correlated with worldwide thunderstorm activity, while the diurnal variation of the mean square levels correlated with local thunderstorm activity. When few local thunderstorms occur during a season, the cumulative distributions of the 250-s samples for the magnetic field intensity could be approximated by a log-normal distribution almost to the 1-percent exceedance level.

INTERFERENCE AND ENVIRONMENTAL IMPACT

Valentino and his colleagues recognize the Navy's proposed ELF communications system that uses an earth-return circuit to excite the earth–ionosphere cavity represents a potential electrical interference problem. As they point out, the electromagnetic fields produced by Sanguine could influence other systems such as power distribution lines and telephone circuits, and other very long electrical conductors. They describe this interference potential and the techniques useful in mitigating it.

Benedick and Greenberg provide an overview of their laboratory and field studies, completed and in progress, designed to disclose possible effects on organisms of a Sanguine system. They indicate that the ELF electric and magnetic field levels associated with a Sanguine system are about 0.07 V/m and 0.2 gauss, respectively, at the surface of the earth directly above a buried Sanguine antenna. They have attempted to determine whether adverse biological or ecological effects could be expected from exposure to these low levels. Research results to date show no indication that exposure to ELF field levels associated with a Sanguine system would have *any effect* on biological or ecological systems.

AN ALTERNATIVE TO PROJECT SANGUINE

Davis and Willis propose an alternative low-data-rate system that could operate at an even lower frequency. For example, at about 0.5 Hz, attenuation in seawater to a depth of 100 m would be only 2.5 dB compared with 25 dB for 50 Hz. A communications system operating at this ultralow frequency thus would enjoy an advantage of more than 20 dB over even a Sanguine system in the criterion of loss in seawater. For receivers at 300 m depth, which may well be reasonable for foreseeable submarine technology, this advantage would be nearly 70 dB and could outweigh any advantage in information bandwidth possessed by the ELF system. The authors describe how the generation of waves in this band might be possible. Methods involve the modulation of ionospheric conductivity from the injection of plasma clouds into the ionospher and heating of the lower E region with powerful radio transmitters. They also consider nonlinear processes in the magnetosphere resulting from cold plasma injection and VLF/ULF three-wave interactions. Rather than travelling in the earth-ionosphere waveguide, most of the energy in the generated ULF signal would be ducted more or less along the geomagnetic field lines in the magnetosphere.

Some Early Historical Aspects of Project Sanguine

JOHN MERRILL

Abstract—**Early extremely low-frequency (ELF) research and the implementation of Project Sanguine to meet the Navy's need for secure transmission to submerged fleet ballistic missile (FBM) submarines are outlined. The 1963 "Intensive Test," which proved the feasibility of ELF reception by a submarine at operational depths, is highlighted.**

INTRODUCTION

IN April 1963, the Navy conducted a communication demonstration between a shore-based extremely low-frequency (ELF) (30–300 Hz) radio transmitter located in North Carolina and a nuclear submarine operating, at a range of 3200 km, with its receiving antenna near keel depth. Termed the "Intensive Test," this event established the fact that a deployed submarine could receive messages from the continental United States (CONUS) without severe reductions in the submarine's operational capability during reception. This was a most important "first" in the history of submarine communications, and this paper describes some of the technical and organizational developments that made the 1963 communication demonstration possible.

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HISTORICAL ORIGINS OF ELF (TO 1958)

This section, taken directly from a paper [1] by Wait of the University of Colorado, briefly summarizes the development of the ELF concept prior to the Navy's interest in ELF transmission as a submarine communications technique.

> "The current Sanguine transmitting antenna is to be powered by a series of generators located along a parallel array of insulated cables buried at depths of the order of 6 ft. These cables are to be up to 160 mi in length, and "grounded" at their endpoints. In order to achieve omnidirectionality, a second array is envisaged that

is located at right angles to the first. The principle of operation of such groundtype antennas has been known for a long time. The basic theory goes back to Sommerfeld [2], who in 1909 and 1926 published a pair of remarkable papers on the exact integral solutions for the fields of dipoles. Of course, the Sanguine antenna is not a Hertzian dipole, but it can be conceived of as a superposition of such dipoles laid end-to-end. In fact, the radiation from such a structure was demonstrated by Beverage and his colleagues in the early twenties, and their results were published in an important but often overlooked paper [3]. Contrary to simple intuition, such a grounded dipole radiates predominantly vertically polarized groundwaves. In the "Beverage wave antenna," the excitation is of a traveling-wave nature, so the pattern is directional. For a center-fed structure, the familiar figure-of-eight pattern results. The horizontally polarized radiation, while always present, is orders of magnitude smaller than the verticaly-polarized radiation—at least, this is the case for VLF and ELF. An interesting feature of these grounded antennas is that they radiate best over poorly conducting ground.

"Now in the Sanguine system, the ionosphere plays a dominating role. Thus, the vertically polarized radiation from the grounded antenna structure couples into the terrestrial waveguide formed by the earth's surface and the lower portions of the ionized layers in the upper atmosphere. As envisaged by Schumann [4], the whole air-earth-ionosphere space acts as a resonant cavity. The fundamental frequency is approximately 8 Hz when account is taken of all the complicating influences. "The remarkable propagation characteristics of ELF waves were exhibited in a very significant study by Chapman and Macario [5]. They used the audio-frequency electromagnetic signals from lightning as their source. Such signals, when received at a distance, are known as atmospherics, or just simply "sferics." The manner in which the frequency spectra change with distance can be used to ascertain attenuation rates. Chapman and Macario found, for example, that, at 100 Hz, the attenuation rate was only of the order of of 1 dB per 1000 km of path length. No wonder such signals will envelope the globe and lead to cavitylike resonances! Using more refined techniques employing multistation observations, Jean *et al.* [6] confirmed these results. Only simple waveguide theory was used to interpret these early data. But even then, it was recognized that a homogeneous and sharply bounded isotropic ionosphere model was not adequate. Thus, Wait [7] introduced exponential models for the electron density and considered the influence of the earth's magnetic field and antipodal focusing effects. A more refined exponential model was then considered by Galejs [8]. Many related investigations were reported in the literature for the next ten years. The reader is referred to two textbooks [9], [10] that include summaries and bibliographies for the propagation theories."

NAVY RESPONSE TO POLARIS COMMUNICATION NEEDS

From 1958 to 1962, a wide spectrum of technical efforts were sponsored by the Navy to improve submarine communications for the then forthcoming fleet ballistic missile (FBM) submarines. Since these submarines were to be deployed at great distances from the United States, they required reliable transmission of strategic orders in order to ensure their survivability as a deterrent force. Some of the objectives of the new communications needs included the following.

1) Error-free one-way communication from the National Command Authority to submerged submarines in their operating areas.

2) Hard copy in the submarines within a fixed period of time.

3) Facilities located within CONUS.

4) No disclosure of the locations of the submarines or exposure to detection.

5) A system meeting a specified submarine speed and depth.

6) No severe reduction in the speed or maneuverability of the submarines.

The exploratory development work was supported by the Bureau of Ships, the Polaris Special Projects Office,[1] and the Office of Naval Research (ONR). The scope of the contracted work included analysis, laboratory, and field work for a diverse variety of potential communication techniques.

The Polaris Command Communications Committee (PCCC) was established as a reviewing, evaluating, and recommending authority for the Navy-sponsored industrial effort. The PCCC was part of the Polaris Steering Task Group and, from 1962 to 1964, was under the sponsorship of the Polaris Communications Office (SP204 of the Polaris Special Projects Office). The committee was chaired by a Navy officer and included a broad representation from Government, industrial, and educational activities. The PCCC met at two-month intervals, with more frequent meetings by the various panels and working groups as required.

In the summer of 1958, N. Christofilos of the University of California, Livermore, Calif., during a briefing by the Polaris Special Projects Office, became aware of the Navy's requirement to communicate from CONUS to a deeply submerged submarine. In August 1958, he proposed the use of an ELF electromagnetic wave in the range 10–100 Hz. In this first approach, the idea was to resonate the earth-ionosphere cavity at its natural modes. At that time, information on the Q of the cavity and data on the atmospheric noise level at the frequencies of interest were scarce.

The Navy immediately took an intense interest in ELF

[1] The Polaris Special Projects Office was established within the Navy Department in 1955 to manage the development of a sea-based ballistic missile weapon system.

transmission because of the following characteristics of such a system.

1) Low attenuation in sea water.

2) Low propagation attenuation.

3) Comparatively low sensitivity to atmospheric disturbances caused by nuclear blasts.

4) Better survivability against nuclear attack (ELF transmitters and antenna arrays lend themselves to dispersion and hardening).

The impact of Christofilos' early concept had several results.

1) ONR supported some immediate investigations of various parameters of the Christofilos concept.

2) The Institute of Defense Analysis called a conference in June 1959 to discuss the credibility and feasibility of the hypothesis. The central idea of the Christofilos concept passed the scrutiny of those present.

3) The Bureau of Ships, in its negotiation of the PANGLOSS[2] contract with RCA Laboratories, incorporated work aimed at exploring the potentialities of ELF transmission. The work included atmospheric and submarine noise measurements and an intermediate-scale experiment.

Under the PANGLOSS contract, RCA was to provide technical and administrative services and prototype equipment in support of the examination of current and future communications systems for the rapidly evolving Polaris program. The program at RCA involved the full-time assignment, on a task force basis, of up to 100 senior RCA scientists and engineers. The primary forces leading to the 1963 Intensive Test were this ELF work conducted under the PANGLOSS contract and various system concept refinements introduced by Christofilos, whose efforts continued to stimulate the submarine communications community until his untimely death in September 1972.

The Navy Underwater Sound Laboratory, New London, Conn., by direction of the Bureau of Ships, was designated Lead Laboratory for PANGLOSS and participated closely with RCA during the life of the contract. The PANGLOSS effort was well documented and was disseminated broadly within the Government and private industry. There were frequent reviews and presentations to the many activities involved in the Polaris effort, with the PCCC the chief forum of technical exchange, debate, and clarification.

NAVY-SPONSORED ELF RESEARCH

At the beginning of 1959, when the PANGLOSS contract started, although there was awareness of the advantages and possible feasibility of the use of ELF for Navy communications, much data were needed to support the concept:

1) Data regarding ELF signal propagation losses;

2) Data regarding the Q of the earth-ionosphere cavity resonances; and

3) Estimates of the atmospheric noise at ELF.

[2] PANGLOSS is an arbitrary designation without intrinsic meaning.

To evaluate the signal propagation characteristics of ELF, propagation measurements were made to obtain estimates of the attenuation as a function of frequency. From March to June 1960, the Navy VLF transmitting antenna at Oso, Washington (Jim Creek), was excited in the frequency range 600–4000 Hz with a 120-kW transmitter (radiating 1–100 W). The Jim Creek antenna is a catenary suspended over a valley. The signal measurements verified the zero-order-mode propagation model and provided a signal attenuation estimate.

The Jim Creek antenna presented a capacitive load to the experimental transmitter, and the upper value of operating current was limited by corona considerations. From this and other considerations, it was concluded that looptype transmitting ELF antennas would be superior to either short vertical or capacitive impedance types. One looptype could be a horizontal wire grounded at the ends and center fed. For this configuration, the radiated field would be determined by the length of the horizontal wire, the current through it, and the conductivity of the earth beneath it.

During June 1960, at an MIT Lincoln Laboratory field site in Ipswich, Mass., radio noise was measured in the frequency band 5–45 Hz. The Q of the earth-ionosphere cavity obtained from these measurements indicated a value of the order of 4 at the fundamental mode [11].

In August 1960, based on the results of the Jim Creek experiment and the MIT-LL findings, the Navy ELF community rejected the concept of using the earth-ionosphere cavity resonance since the Q from both field measurements was too low (4–5) to provide communication by exciting cavity modes. The Navy now visualized a traveling-wave mode excitation and the use of a more efficient transmitting antenna, i.e., a horizontal wire grounded at the ends over a poorly conducting ground. Christofilos agreed with these changes, but perhaps more importantly, he examined ELF from the standpoint of a complete system. His investigations established that, at a comparable cost, an ELF system consisting of a series of wires erected over poorly conducting earth can achieve a performance substantially greater than VLF (~15–25 kHz) normalized to ELF data rates.

In October 1960, the concept of an ELF communication signal source using a grid of horizontal center-driven end-grounded transmitting antennas was unanimously recognized as an avenue for further investigation. This conclusion was reached after experimental and theoretical investigations performed primarily by the RCA David Sarnoff Research Center at Princeton, N. J., and work done by Christofilos at the University of California.

At the request of the PCCC, an ELF committee was formed in January 1961 to assess the research and development plans for ELF. This ad hoc committee included members from the Stanford Research Institute, the Navy Underwater Sound Laboratory, the Development Engineering Corporation (DECO), the Naval Research Laboratory, and the Bureau of Ships.

In May 1961, the ELF committee recommended a

"decisive experiment" that would provide the most realistic technical and economic approach for an operational system. The experiment specified the implementation of a complete ELF radio system consisting of a transmitter located in a region of low earth conductivity (2.5×10^{-4} Ω/m), a 100-mi (161-km) antenna, and sufficient input power to provide an electric field of 58 μV/m at a distance of 1000 km. The PANGLOSS contract was extended to include a system study for the radiation and reception of ELF signals and a site survey for an experimental transmitting antenna. In support of the experiment, ONR sponsored studies of atmospheric noise and earth conductivities to determine the characteristics of these phenomena, develop instrument criteria, and set standards for measurement methods. The decisive experiment was scheduled to be completed by March 1964.

Concurrent with the ELF transmitting facility built and tested under Project Sanguine,[3] ONR sponsored the lease of a 60-Hz high-voltage transmission line as a signal source for a propagation experiment. The power line extended from Cheyenne to Laramie, Wyo., a distance of about 70 km. At night, the line was disconnected from its normal loads, suitably grounded, and driven at 60 Hz. A farfield receiving site was located in the Los Padres National Forest, Calif., about 1500 km from the power line in Wyo. Nearfield measurements and correlation of radiation with earth conductivity measurements at the transmitting antenna were also part of this investigation. This work was performed by DECO of Boulder, Colo.

THE INTENSIVE TEST

The Intensive Test was that portion of the ELF decisive experiment in which a concerted effort was made by numerous activities to obtain the data necessary to verify theoretical predictions and provide increased confidence in specifying design parameters.

A site conductivity survey made for the test in western Virginia and western North Carolina resulted in a 176-km antenna design. The south ground of the transmitting antenna was located in a lake at Lookout Shoals, N. C., and the northern ground was located in a large tobacco field at Algoma, Va. This antenna was actually in use periodically from 1962 until 1970 and was referred to as Site Alpha (Fig. 1). The antenna was center fed by a transmitter consisting of a 120-kW shaker-table amplifier driven by a special keyer-modulator unit. The antenna and transmitter were completed in December 1962, and during the following weeks, various local compatibility problems were resolved. The transmission frequencies used were primarily between 4 and 500 Hz; above 150 Hz, power was drastically reduced to minimize interference with local telephone service. The antenna current for most operations at or below 150 Hz was a nominal 60 A.

[3] Sanguine or Project Sanguine is an arbitrary designation first applied to ongoing ELF research by the Bureau of Ships, Communications Systems Branch, in 1962. The term continues to designate work directed toward the implementation of an ELF shore-ship radio communication system.

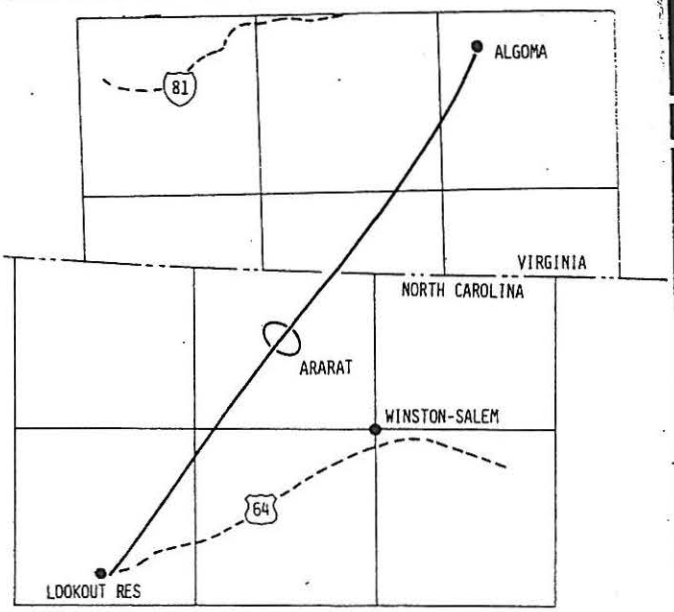


Fig. 1. Site Alpha (in use 1962–1970).

TABLE I

Early Sanguine Chronology

1955	Polaris Special Projects Office established.
1958	Industrial briefings for new communication systems. First Nicholas C. Christofilos ELF concept (August).
1959	PANGLOSS starts at RCA. Institute of Defense Analysis conference on Christofilos concept (June).
1960	Jim Creek 600 to 4000-Hz propagation experiment. Balser–Wagner measurements of earth-ionosphere cavity resonance (June). Second Nicholas C. Christofilos ELF concept (August).
1961	Ad hoc ELF committee makes its decisive experiment recommendation (May). Decisive experiment implementation starts.
1962	DECO ONR-sponsored ELF propagation experiment, using 60-Hz power line; reception at 1500 km (June–August). Sanguine decisive experiment ELF system operative (December).
1963	Intensive Test measurements (January–April). Intensive Test at sea measurements (January–February). Intensive Test report completed (April 17).

Three receivers, each with an integration time of 5 min, were constructed to use in fixed, in land-portable, and in submarine installations. The data collected during the Intensive Test resulted in further validation of the zero-order-mode propagation model at frequencies below 600 Hz and provided accurate attenuation data down to 78 Hz. Fig. 2 presents the various Intensive Test site locations.

In addition to the propagation investigations, six weeks of communication tests (starting January 21, 1963) were made with a receiver installed on the USS SEAWOLF (SSN-575). The submarine was equipped with a 1000-ft trailing cable, at the end of which was an electric probe-

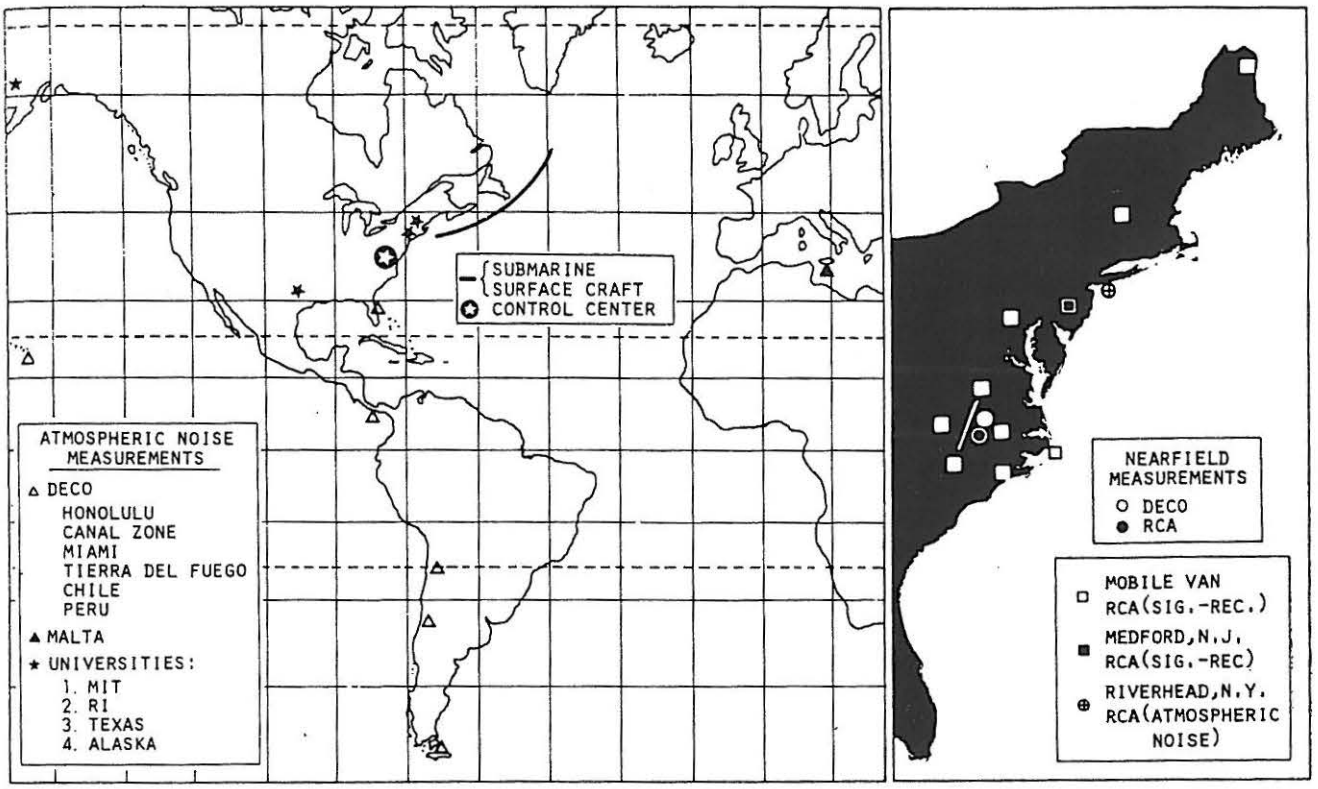


Fig. 2. Intensive Test site locations.

pair sensor with a 75-m probe separation. Signals at 78, 125, 156, and 250 Hz were measured at ranges up to 3200 km with the trailing antenna at keel depth. Signals were received at a range of 850 km with the antenna at greater depths. The power radiated from the experimental transmitting antenna was of the order of 1 W.

Table I lists some of the key events that led to this successful demonstration of the feasibility of ELF transmission from CONUS to a submarine at an operational depth, speed, and range.

PRESENT STATUS

Project Sanguine is now in the Validation Phase of its implementation. This current phase of the Navy program for implementing the ELF system will result, in 1975, in a competitively derived system design suitable for entry into prototype development.

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John Merrill was born in Buffalo, N. Y., on February 12, 1917. He received the B.A. and M.Ed. degrees from Hillyer College of the University of Hartford, Hartford, Conn., in 1953 and 1956, respectively. He also studied engineering at the University of Connecticut, Storrs, and the University of Buffalo, Buffalo, N. Y.

From 1944 to 1951, he was an Instructor in Electronics at the U. S. Coast Guard Radio Engineering and Maintenance School, Groton, Conn. Other teaching affiliations have included the Department of Electrical Engineering of the University of Buffalo, Hillyer College, Mitchell College, and the Ward School of Electronics, Hartford, Conn. He was an Electronics Scientist in the Electromagnetics Division of the U. S. Navy Underwater Sound Laboratory, New London, Conn., from 1954 to 1959. His work was primarily concerned with UHF and microwave antenna development. He was a Staff Member and Project Director at the Research Division of Radiation, Inc., Orlando, Fla., from 1959 to 1960. He returned to the Underwater Sound Laboratory in 1960 as a Senior Project Engineer, investigating phenomena in the VLF spectrum. In 1967, he was appointed Program Manager for the Laboratory's Sanguine effort, a position he currently holds.

Mr. Merrill is a member of Phi Delta Kappa and was chairman of the Connecticut Valley Section, IRE, from 1952 to 1953.

Early Development of the Project Sanguine Radiating System

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Abstract—**The Project Sanguine system is the result of many years of research and analysis into radiating system configurations. The paper describes the early portions of this search, the recognition of equivalences among several of the candidate systems, the conduct of an early transmission experiment, and the initial efforts at system optimization and choice of the radiating system configuration. The early research and tests provided confirmation of the theory that a vertically polarized *E*-field propagates through the earth ionosphere cavity at ELF with a slight forward tilt which allows it to enter the sea water and then penetrate to considerable depths. It also verified the behavior of the earth return antenna element through the operation of an experimental system. In addition, a system optimization program was developed to allow the cost of achieving various levels of system performance to be assessed.**

I. INTRODUCTION

THE objective of Project Sanguine is communication from the continental United States to submarines at depths of hundreds of feet anywhere in the world. Early research considered various means of accomplishing this objective, such as the use of buoy relays, seismic effects, etc. The method selected for engineering development was direct electromagnetic transmission at extremely low frequencies, or ELF, (carrier frequencies on the order of 30–100 Hz) because this method provides the desired degree of operational flexibility and can be implemented to provide global coverage to the desired ocean depths.

The Project Sanguine radiating system consisting of a grid of long horizontal antennas grounded at each end and series excited was the outgrowth of years of careful research and analysis. Starting with a thorough search of prior art in 1959, consideration was given to a number of ways in which the objectives of the project could be achieved. Among them, the concept of using ELF was in the fore from the very beginning because of its low sea water attenuation. However, in terms of spectrum decades, ELF is as far removed from the medium frequencies (MF) used for AM radio broadcast as MF is removed from some of the microwave frequencies used for point to point transmission. Thus the techniques for transmission of ELF, as well as our usual concepts of radiation efficiency, turned out to be vastly different compared to the way they are thought of at MF, just as MF techniques differ considerably from microwave techniques.

Initially the mechanism of coupling of energy from the transmitting antenna into a propagation path and then into the sea was not well understood. Various ideas existed and, correspondingly, various techniques were proposed for investigation. In this paper, the proposed techniques will be divided into several categories for description. First are those that depended on some method other than direct transmission, such as the use of a relay vehicle like an earth satellite or a frequency conversion in the ionosphere (Luxembourg Effect). Next were methods involving direct transmission, but via the direct generation of a vertically polarized electric field. Such methods required the use of huge vertical radiators. Then there were methods partially or fully equivalent to the long horizontal wire antenna finally selected for engineering development. These included the island slot, the mountain supported loop, and the long horizontal wire itself.

Although this paper is devoted to the early development of the Project Sanguine radiating system, it is helpful to note the propagation mechanism briefly here because of its effect on antenna development. A key exposition of this propagation mechanism was published by Wait in 1961 [1]. In it Wait pointed out that the earth and ionosphere act as a waveguide through which radio energy propagates. At ELF, only the zero-order mode is significant. Propagation occurs with a vertical electric field accompanied by a horizontal magnetic field. This is approximately TEM-mode propagation between parallel conducting plates. However, losses in both the earth (or sea water) and the ionosphere cause bending or "tilt" of the wave front toward the lossy medium and, consequently, a horizontal E field at the surface of the earth (or sea water) as well as at the ionosphere. Thus in terms of radiating antennas on land and receiving antennas in the water, the E field is parallel to the earth's surface while, for distant propagation from transmitter to receiver, the E-vector is predominantly vertical.

The horizontal antenna along the surface of the earth produces a horizontal E-vector. Because there exists a vertical loop-shaped return current path beneath the wire (in the ground) a horizontal H-vector also is generated. We may view this horizontal H-vector as propagating parallel to the surface of the earth. The horizontal E-vector initially propagates upward, but bends (diffracts) to become vertical, thus producing the wave propagating in the earth–ionosphere cavity. Any such wave actually tends to propagate with a slight forward tilt at the surface of the earth (or sea water) and thus has a slight, but useful horizontal component which, together with the horizontal H field, enters the sea water.

Manuscript received October 17, 1973. The work reported in this paper was performed while the author was at RCA Laboratories, Princeton, N. J.

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The basic equation for the vertical E field is

$$E_z = \frac{ILf}{2h_i}\left(\frac{2\mu_0 S_0}{c\sigma_e}\right)^{1/2}\left(\frac{1/a}{\sin r/a}\right)^{1/2} \exp(-\alpha r)\cos\theta$$

where

- E_z vertical E field (volts/meter);
- f frequency (hertz);
- I antenna current (amperes);
- L antenna length (meters);
- h_i effective ionosphere height (meters);
- μ_0 permeability of free space $= 4\pi \times 10^{-7}$ H/m;
- S_0 parameter arising in mode solution in earth-ionospheric cavity;
- c velocity of light $\approx 3 \times 10^8$ m/s.
- σ_e earth conductivity (mhos/meter)—typically 10^{-2} to 10^{-4} mho/m;
- a radius of earth $= 6.4 \times 10^6$ m;
- α attenuation rate in air in dB/meter—typically 0.4×10^{-6} to 2.5×10^{-6} at ELF;
- r distance from source (meters);
- θ angle subtended by line from observation point to source center and by antenna direction line.

The real part of S_0 can be neglected for most purposes relative to its imaginary part, in which case

$$c/v_{\text{phase}} \approx jS_0$$

where v_{phase} is the phase velocity of the wave and where c/v_{phase} is typically 0.5–1.0 at ELF.

The horizontal electric field E_x at depth d is

$$E_x = E_s\left(\frac{2\pi f\epsilon_0}{\sigma_s}\right)^{1/2} \exp(-\alpha_s d)$$

where

- ϵ_0 permittivity of free space $= 10^{-9}/36\pi$ F/m,
- σ_s conductivity of sea water (mhos/meter)—typically 3 to 5 mhos/m,
- α_s attenuation rate in sea water in dB/meter—about 0.3 at 75 Hz.

Note:

$$\alpha_s \propto f^{1/2}.$$

The basic research and analysis led to the conduct of a "decisive experiment" using a 109-mile long antenna in North Carolina and Virginia in 1962. This experiment proved successful in that it provided experimental verification of the theory that had been developed. In addition it validated the data being used in a systems optimization program whose purpose was to establish the basic design parameters of the minimum cost system to meet a preset group of performance criteria.

The sections to follow describe the search for a radiating system configuration, the recognition that some of the candidate systems were equivalent, the conduct of an early transmission experiment, and early efforts toward the choice of the radiating system configuration.

II. SEARCH FOR CONFIGURATION

The research toward the Project Sanguine system of the late 1950's and early 1960's has been noted in several recent papers [2]–[4]. Although many physical phenomena for accomplishing Project Sanguine objectives were considered, this writer is most familiar with the electromagnetic wave approach which, in time, was selected because of its cost-effectiveness.

One of the initial tasks was a study of the past literature, especially that dealing with the generation, radiation, and transmission of electromagnetic waves in the ELF region of the spectrum known to penetrate sea water well. Since the generation of such signals involved the use of well-established audio frequency techniques and super-power audio frequency amplifiers, most of which were well known, the work concentrated on means of radiating ELF (to be discussed in the following) and on the signal attenuation and noise levels to be expected along the path and at the receiver.

During the years prior to 1962, no radiating system existed to enable signal attenuation over the earth's surface to be measured, so the researchers had to rely on theoretical developments, such as those of Wait [1] and Schumann [5], as well as on the results of tests that had used sferics [6] as the signal sources. Although less than desired, there was sufficient correlation between theory and sferics observations to lend credence to the concept that the attenuation of ELF signals over the earth's surface is quite low.

Much less was known about the noise level in the receiving environment. However, sferics again served as good natural signal sources, against which to compare received noise levels due to submarine machinery, surface potentials, and water motion and bubbling. In addition, the search for a low noise submarine receiving antenna, involving tests with orthogonal loops, insulated wires, and exposed electrodes, finally showed the best submarine receiving antenna to be one with the most widely possible spaced exposed electrodes trailed as far away from the submarine as possible.

As noted previously, the transmission path into the sea water involves a horizontal E- and a horizontal H-vector. A pair of spaced horizontally deployed electrodes thus will intercept the E-field. The greater their spacing, the more received voltage, V_r, at their terminals, since

$$V_r = lE_x$$

where l = electrode spacing (meters).

By trailing these electrodes as far away from the submarine as possible, noise due to water turbulence around the hull as well as onboard machinery is minimized. Loops to sense the H-field were tried, but H-field signal-to-noise ratios were found to be lower than E-field signal-to-noise ratios, probably because of onboard machinery; consequently, the probe pair was selected.

The development of the submarine receiving antenna

paralleled, to an extent, the development of the transmitting antenna. In both cases various configurations were tried, some were found equivalent, and the horizontal wire, exposed at each end to the conducting medium, proved to be the best configuration for both transmitting and receiving.

The transmitting antenna itself, because of the extremely long wavelengths involved (3 Mm at 100 Hz, for example), was early recognized as the chief development and design challenge. But what configuration would enable the radiation of a sufficient field strength for global reception at operational depths, even with many megawatts of input power?

The antenna obviously had to be very small in terms of wavelength, so "small" antennas, surrounded by dielectric and magnetic materials, were considered. However, such loading was found by analysis simply to provide a better antenna terminal impedance by matching the antenna to the surrounding medium (air). The cost of even small quantities of such "loading" material proved to be prohibitive, so the developers and designers had no alternative but to "think big." The results were the following antenna concepts:

nonlinear mixing in the ionosphere (Luxembourg effect),
trailing wire from earth satellite,
excitation of the magneto-ionic duct (to be described later),
helicopter-suspended wire,
spiral-top-loaded antenna,
island slot,
mountain loop,
beverage antenna.

The systems/methods have been listed in what this writer feels are the least to the most feasible, the beverage antenna element finally having been chosen as the prototype for the Project Sanguine antena array.

A. Nonlinear Mixing

A phenomenon first observed in the vicinity of the high-power European broadcast station, Radio Luxembourg, is the nonlinearity of the ionosphere when subjected to very high field intensities [7]. The concept: generate an ELF wave in the ionosphere by establishing two medium frequency transmitting systems in close proximity to one another, and having a frequency separation equal to the desired ELF frequency. A search of the literature dealing with the Luxembourg effect, however, soon showed that the magnitude of the effect is so small that it is essentially worthless as a practical ELF radiating system; hence, this concept was discarded.

B. Trailing Wire

A sufficiently long wire (i.e., approaching $\lambda/10$ or more) should be a reasonably efficient radiator, and should not require extremely high voltages to excite it because it should have a reasonably good ratio of radiation impedance to driving point impedance. Trailing wires from aircraft (see Fig. 1) had been used with some success as VLF radiators but have the disadvantage that they are largely horizontal, whereas we desire a vertically oriented electric antenna to excite an ELF field in the earth–ionosphere cavity for the reasons described previously, and horizontal antennas at aircraft heights do not meet the excitation requirements. Consequently, consideration was given to deploying a wire many miles long from an earth satellite. Such a wire could be expected to assume the desired vertical orientation with respect to the surface of the earth because of gravity gradient effects. However, several serious drawbacks presented themselves: (1) the radiated field would have to penetrate the entire ionosphere, whose total attenuation to ELF is not known; (2) radiation from the ends of the antenna probably would be zero or very small, thus producing no field directly under the satellite; (3) the transmitter power would have to be limited to tens of watts at most, based on the state of earth satellite system art in the time frame of the early 1960's and based on our ability to forecast it for the decade beyond. For these reasons, consideration of trailing wires from earth satellites was abandoned.

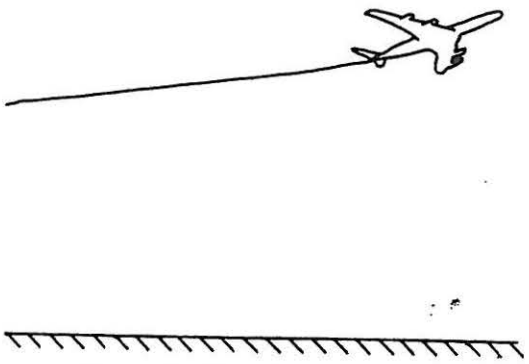


Fig. 1. Trailing wire from aircraft.

C. Excitation of the Magneto–Ionic Duct

Theoretical work, coupled with experiments using sferics, led to the observation that good transmission paths exist in the 1–6 kHz region, between conjugate points on the earth's surface. The transmission time was found to be a function of frequency, as evidenced by the fact that the sferics, when received by this path, manifested themselves as "whistlers," having an ascending or descending pitch as a function of time. This indicates that the best transmission path is a function of frequency. Although interesting from an academic viewpoint, transmission via the magneto–ionic duct did not appear practical for Sanguine because only a relatively small area of good reception exists for a given transmitter location and because the frequency range over which most duct transmission could be observed was somewhat higher than that which would permit the good sea water transmission desired for Project Sanguine.

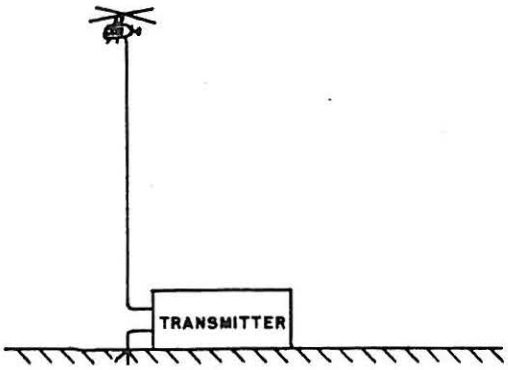


Fig. 2. Wire suspended by helicopter.

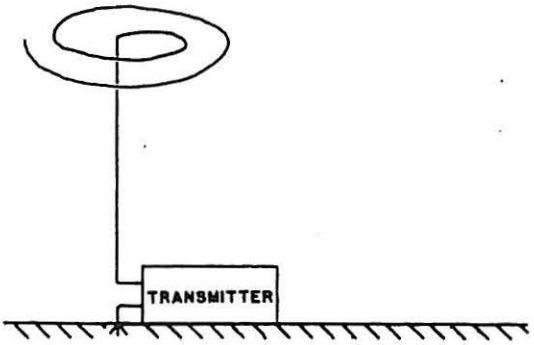


Fig. 3. Spiral top loaded antenna.

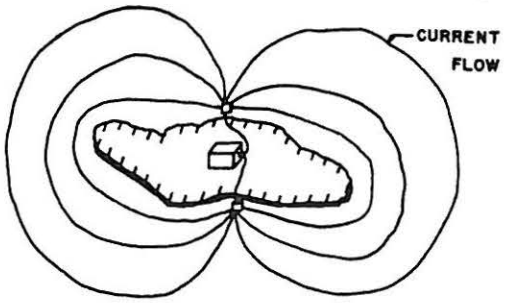


Fig 4. Island slot.

D. Helicopter-Suspended Wire

The possibility of using transmission modes other than one in which a transverse electromagnetic wave (vertically polarized E-vector) propagates over the surface of the earth did not appear attractive for the reasons already cited. One radiating system for producing a vertically polarized E-vector would be a very tall vertical antenna between the earth and the ionosphere. A long vertical wire suspended by a helicopter (see Fig. 2) thus might be usable. It would have the advantage of portability in that the transmitting equipment could be located either on land, in a group of trailers, or on a ship at sea. Thus even relatively low radiated powers could be used since a lack of coverage area could be compensated by the use of more radiating systems in some of the most desired locations. However, aside from the strategically dubious value of such an arrangement, the helicopter-suspended vertical wire did not prove practical because of the amount of weight of wire that can be lifted by the largest helicopters to a significant height, coupled with the tensile strength limitations of wire itself. Thus wire strong enough to support its own weight could not be suspended from a great enough height (several miles) to produce an effective radiator. The relatively small heights feasible (thousands of feet) resulted in such low radiation resistances (fractions of an ohm) at ELF that producing a significantly high current in the antenna called for dangerously high voltages (over 50 kV) at the base of the antenna. Consequently, consideration of the helicopter-suspended wire was discontinued.

E. Spiral-Top Loaded Antenna

One of the more serious disadvantages of the helicopter-suspended wire was the very high capacitive reactance at its base, which required the use of a large (and thus lossy) loading inductor. This disadvantage led to the concept of the spiral-top loaded antenna [8], which is a vertical antenna having a top load in the form of a spiral providing both series inductive and shunt capacitive loading in one element. Experimental work on models of this antenna showed that its reactance is that of an open transmission line in the vicinity of resonance and at lower frequencies. The length of the spiral is approximately the length of the open transmission line whose reactance it exhibits. Consequently, hundreds of miles of wire would have to be elevated to a great height to use this antenna concept at ELF. However, it comes closer to having the desired characteristics than the antennas considered earlier in that a number of vertical members can be operated in parallel, all sharing a common spiral top load (see Fig. 3). However, because of the massive aerial structure required for ELF radiation, this antenna was not given further consideration for Project Sanguine uses.

F. Island Slot

Since the transmission of ELF electromagnetic energy to submarines involves the flow of ELF currents through the water, the concept of "surface current" transmission was developed. This involved the use of an island or peninsula, across which an ELF current was made to flow, with its return circuit through the water (see Fig. 4). Early tests were performed across eastern Long Island with probe-pair receiving electrodes. Initially, the concept was that the current would flow through the water from one electrode around the end of the island and back to the other. This path was found to exist. However, current also returned through the earth along the path of the existing wire connecting the electrodes. Further tests and theoretical development showed that the current path through the water could not be relied upon for transmission over any significant distance horizontally. However, the existing wire connecting the electrodes was found to act as a small beverage antenna (see Section H).

G. Mountain Loop

Recognition of the vertical E, horizontal H mode of propagation of ELF over the surface of the earth led to

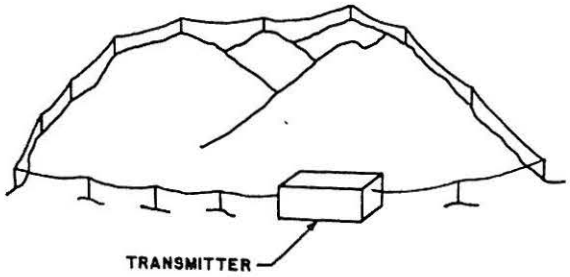


Fig. 5. Mountain loop

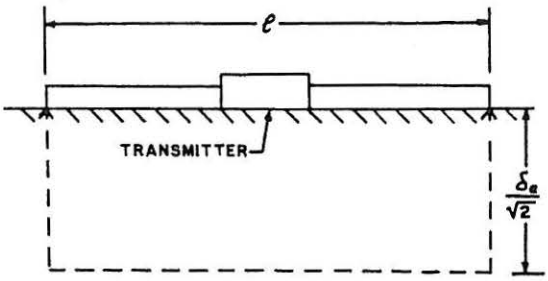


Fig. 6. Loop equivalent to Project Sanguine antenna element.

studies of the feasibility of a large loop antenna with its axis horizontal. Such a loop might be supported by a mountain in order to increase its cross-sectional area. (See Fig. 5.) A loop can be fed much more easily than an electric dipole or monopole because no tuning inductors with their inevitable loss are required, nor does a loop need a ground system. Computations showed, however, that a cross-sectional area on the order of several hundred square kilometers would be required in order to achieve the desired amount of radiation from transmitters of feasible power. Moreover, multiple-turn loops of such size had undesirably high inductive reactance from a coupling viewpoint. Although mountains generally provide means of lifting wires above average terrain, they provide no way of allowing the return circuit to be run, unless the mountain happens to have a conveniently-placed tunnel!

H. Beverage Antenna

The mountain loop and the island slot, in particular, have one thing in common: both carry current through a wire that parallels the ground or local terrain. The current return of the mountain loop is by way of a wire path whereas the current return of the island slot is by way of the water although, as noted in the discussion of the island slot, current also returned through the earth along the path of the existing wire connecting the electrodes. The beverage antenna, as described in the literature, normally is a horizontal antenna several wavelengths long used for receiving signals by abstracting energy from passing waves as a result of the wave tilt that the earth losses produce in vertically polarized waves traveling along the surface of the ground. The significant factor is its use of the wave tilt. The greater the "earth losses" the greater the wave tilt, and the more effective the beverage antenna. Because of its relatively low efficiency but good directional characteristics, the beverage antenna found use as a receiving, rather than a transmitting, antenna at VLF. However, as frequency decreases, the decreased size of a fixed length beverage in terms of wavelength is partially compensated by the increased "effective depth" at which the return current flows since the depth is $\delta_e/\sqrt{2}$ where δ_e is the skin depth of the earth as a conductor and where the assumption is made that $L \gg \delta_e$. (Generally δ_e does not exceed 6 miles, while L is usually at least 60 miles.) The skin depth is

$$\delta_e = \left(\frac{2}{\omega \mu_e \sigma_e}\right)^{1/2}$$

where

- ω $2\pi f$ = frequency (radian/second);
- μ_e permeability of the earth = μ_0 in the absence of iron deposits;
- σ_e earth conductivity (mho/meter).

The actual phase of the return current differs from that of the antenna current by approximately 45°. This contributes to the reactive component of the antenna input impedance. As will be discussed in the next section, the deep current return path makes the ELF beverage, or Project Sanguine antenna, function as it does.

III. RECOGNITION OF EQUIVALENCES

The field at a distance from any antenna is a function of the current I flowing in each elemental length, Δl, of that antenna. Consequently, certain equivalences can be established among some of the antennas described previously. Those equivalences of particular interest relate to the Project Sanguine antenna element, which consists of a long wire parallel to the ground, grounded at each end, and series fed along its length, usually in or near the center. This type of configuration results in a return current flow through the earth at the "effective depth" described above. This return current flow through the earth is a way of getting some free height or loop area. The lower the frequency, the larger becomes the effective size of this antenna. The actual current distribution appears similar to the lines of magnetic force between two poles of a magnet. For the antenna, the current density is greatest closest to the wire and around the ground contacts at the ends.

Fig. 6 illustrates the vertical loop (horizontal axis) equivalent to the Project Sanguine antenna element. The current flow in this antenna makes it equivalent to two verticals of height $AD = BC$ spaced a distance l and fed out of phase. Alternatively, it is fully equivalent to a mountain loop in which all members, AB, BC, CD, and DA are metallic conductors. It is also equivalent to an island slot whose electrodes are spaced a distance l, provided that the ends of the island are sufficiently distant that the current return is primarily back along the length of the wire rather than around the end of the island.

The above equivalences are valid assuming that $l \leq \lambda/4$, generally a very good assumption at ELF. The radiation

pattern of the Project Sanguine antenna is a simple figure eight or "doughnut" pattern characteristic of an elemental dipole antenna.

IV. THE DECISIVE EXPERIMENT

The search for the most cost-effective configuration for an ELF radiating system, together with the recognition that certain of the candidate configurations are equivalent, led to the preliminary selection of the horizontal earth-return element for the Project Sanguine antenna. However, no controlled test of the performance of such an antenna at ELF had ever been performed, and without such a test, doubts existed regarding the overall feasibility of ELF for the transmission of Project Sanguine data. Concern also had arisen over the bulk, or in-depth, conductivity of the earth at various potential transmitting locations because of the conductivity's effect on the depth at which the current would flow from one end of the element to the other. Desirably, this conductivity should not exceed 10^{-4} mho/meter. In addition, the electrical compatability of such a system with nearby power and telephone systems was questioned because induction could cause the test frequencies to modulate nearby power systems, thereby causing lighting flicker and more seriously, could cause inadvertent telephone ringing as well as audible hum or tones in nearby telephones.

For these reasons, a "decisive experiment" was devised in which a complete communication system from a phase-shift-keyed transmitter to an on-board submarine receiver was built on an experimental basis by RCA in 1962. With respect to the radiating system, an important factor was the selection of its location. Not only must the antenna be over earth of low conductivity (10^{-4} to 10^{-5} mho/meter) to several miles depth, but the end of the antenna must be in regions of relatively high (10^{-2} mho/meter or greater) surface conductivity, so that good low resistance grounds would result. To achieve current penetration to the full earth skin depth, δ_e, the antenna should be several δ_e long, desirably on the order of 100 miles or more. If the antenna length is comparable to, or less than, δ_e, the radiated power is still proportional to IL, but the input power must be increased to obtain the current I because the input resistance increases. This increase occurs because the current never gets a chance to spread out.

The search then started for a strip of land having these desired characteristics. The low conductivity requirement, together with the system's undetermined effect on power and telephone systems, kept the search to semirural and rural areas. A complicating factor in this regard, however, was the importance of on-board reception on a submerged submarine, coupled with the rather limited range that could be expected from a single transmitting element excited by a transmitter of moderate power. This meant a location in a low conductivity region, yet within a few hundred kilometers of the shore.

The foregoing considerations led to studies of geological maps followed by earth conductivity tests similar to those described by Martin in a recent paper [9]. The site selection process concentrated on locations within several hundred kilometers of the ocean shore. Based upon this preliminary work, a strip of land extending from a point near Catawba, N.C., to a point near Algoma, Va., was selected. The transmitter was placed near the center of the strip, near Ararat, N.C. Ground systems with radials several kilometers long were installed at the end sites to provide ground contact resistances on the order of one to two ohms. The antenna consisted of three Gauge 4/0 conductors paralleled for low resistance (about 8 ohms) and reactance. The transmitter consisted of a specially designed minimum phase shift keyer and oscillator, capable of generating carrier frequencies in the 15–260 Hz range. The amplifier was a 10 kW unit that had been designed for vibration table service. The receiver used a probe-pair receiving antenna and low noise paramp circuits.

Initial transmitter tests were performed in coordination with power and telephone companies serving the areas along and near the antenna. These tests showed only negligible effect on even the closest power systems, in the form of slight light flicker at the lowest carrier frequencies. The telephone systems, however, were much more seriously affected, especially a few that were still using earth return circuits and special ringer frequencies. As explained previously, induction appeared to be the main coupling mechanism between the antenna and the power and telephone systems. Some of the older telephone systems using earth-return ringer circuits also were subject to conductive mutual impedance coupling to the antenna's earth return currents.

As a result of these tests, certain of the more serious telephone ringing problems were solved on an individual basis, (running wire returns for some ringer circuits, for example), and the more widespread problems were handled by restricting the time and frequency of operation of the system according to a schedule mutually agreed upon between the experimenters and the local telephone companies.

The simplest summary of the results of the decisive experiment is that everything worked as expected. The minimum-phase-shift keyed test signals were detected on-board a submarine operating at a 100-meter depth in the North Atlantic many hundreds of kilometers from the end of the antenna. Various data rates and carrier frequencies were used, with signals being received at the low bit error rates (10^{-3} to 10^{-4}) expected. In addition, land based receiving sites that had been established for sferics measurements (Perrine, Fla.; Princeton, N.J.; and Presque Isle, Me.) also were used to monitor received signal strength to further establish the characteristics of the radiating system and the behavior of ELF propagation over the surface of the earth.

These tests showed that the attenuation increases with frequency, the same as had been indicated by sferics measurements. In addition, the attenuation is lower at night than during the day. For example, at 78 Hz, one of the test frequencies, the daytime attenuation was 1.28

dB/Mm, compared with 1.01 dB/Mm at night. Corresponding values at 156 Hz are 3.12 dB/Mm in the day compared with 1.74 dB/Mm at night. A comparison of these values with attenuation rates obtained from sferics measurements is given by Burrows and Niessen in a recent paper [10]. This comparison shows, in both cases, the lower attenuation at night, as well as the increase of attenuation with frequency.

V. SYSTEM OPTIMIZATION

Having established not only the attenuation rates for ELF propagation over the surface of the earth and into the water to submarine operating depths, but having also established that earth conductivities exist that are suitably low (e.g., 10^{-4} mho/m) to permit the desired antenna performance to be obtained, the next step was "system optimization." This step was taken because of the high cost of any conceivably useful Project Sanguine system. For this optimization process, the system performance parameters were identified as: data rate (bits/s); bit error rate; range (km); depth (meters). Hand computations had indicated that for any specified combination of these performance parameters there exists a minimum-cost system obtained by the optimum selection of the following design parameters.

Antenna element length,
number of antenna elements,
antenna element wire size,
antenna element parallel wires, and
} these factors determine resistance in ohms/meter

ground contact resistance (assuming a radial ground system whose cost effectiveness had been established previously by a separate optimization) is a function of wire length, wire radius, number of wires (radials), depth of burial, earth conductivity at ground area (fixed parameter, dependent on site selection). Other parameters are transmitter power, carrier frequency, noise level in the receiving environment, and modulation technique.

In addition, there are certain parameters that are selectable to an extent, such as earth conductivity under the antenna, but that are not variable during an optimization in a given location. Other parameters, such as height of the ionosphere and attenuation rate, α, over the surface of the earth, are set in as predetermined parameters, α being only a function of frequency.

Each of the design parameters, such as antenna element length and wire size, transmitter power, etc., has a cost associated with it. All of these cost factors also are entered into a computer program containing all of the performance equations and cost factors. As can be appreciated, the entrance of cost factors into the optimization program involved the use of discontinuous functions because of the way in which materials and equipment are priced. This situation was handled by performing an initial optimization using linear approximations to the actual functions. Improved approximations valid over smaller, more appropriate, ranges were then used in second and third iterations to achieve the final optimization.

The systems optimization program uses an iterative gradient technique to minimize system cost [11]. This technique is known as the Newton–Raphson method. It allows system design to be put on a firm mathematical basis where the "best" system can be found automatically from the requirements and constraints specified by the user. It is only as good as the subsystem cost models and the accuracy of the parameters entered into the program, but provides some very useful information, as indicated below. The assumption is made that the basic system configuration is fixed, i.e., the system can be varied only by changing its continuous parameters.

The system optimization program showed that some of the earlier, and quite laborious, hand computations had come within about 10 percent of the optimum system, i.e., a computer optimum was finally found that had somewhat different design parameters, thus allowing about a 10 percent cost saving on a system that had been used as a reference for numerous computations. The real value of the systems optimization program, however, is that it allowed a quick determination of the way cost varies as a function of data rate, error rate, depth and range, or coverage area. Thus for each point on a curve of cost versus depth, data rate, etc., the computer provided all of the numerical parameters for a minimum-cost system.

VI. CONCLUSION

This paper has traced the early development of the Project Sanguine radiating system during the late 1950's and early 1960's. The rationale by which the present radiating element was selected, and the early work in experimental verification of the basic concepts as well as system optimization is described.

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Propagation of ELF Electromagnetic Waves and Project Sanguine/Seafarer

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NYPL

Abstract—Electromagnetic waves at extremely low frequency (ELF) have a remarkable ability to propagate with very low attenuation in the space between the earth's surface and the ionosphere. The resulting fields also are able to propagate to moderately great depths in the ocean in spite of the high conductivity of sea water. The principal drawback in the use of such signals for communication is the inherent inefficiency of the transmitting antenna. But indeed the waves do penetrate to deeply submerged submarines when all other methods fail. This has been the principal motivation of the U.S. Navy's controversial Project Sanguine that envisages a huge antenna facility that could cover an area of 100 by 100 km. This project, now called Seafarer, has stimulated a great deal of research on how ELF waves (in the range from about 1–1000 Hz) propagate. We review here some of the fascinating developments in this field. Actually, the early investigations of Nicola Tesla have a striking similarity to Project Sanguine. Tesla's prophetic lectures and articles provide an interesting historical perspective to the later developments that have spanned over 70 years. After sketching some of the early history of the subject, we outline the theoretical and physical bases of the propagation phenomena. While the basic concept of the earth–ionosphere waveguide is relatively simple, the physics of the interaction with the ionospheric plasma is complicated, particularly during disturbed conditions.

INTRODUCTION

TO MOST electrical engineers, the audio-frequency portion of the electromagnetic spectrum is associated with the distribution of power from generating stations to consumer via wire conductors. The wireless transmission of such energy is not considered to be feasible. Indeed, the CCIR and the FCC do not make any frequency allocations below 10 kHz.[1] In fact, even in the range from 10 to 30 kHz, that is usually described as very low frequency (VLF), enormous transmitting antennas are needed. Nevertheless, there are some interesting possibilities at frequencies even as low as 45 Hz if nonconventional radiating systems are utilized.

It is our purpose to make an overall review of extremely low frequency (ELF) phenomena from the electrical engineer's point of view. To conform with the usage of active workers in the field, ELF will encompass the range from 1 to 3000 Hz.

Without attempting to be comprehensive, we will trace the history of the subject from the conceptional beginnings to the current state-of-the-art. The References are representative rather than exhaustive, although a diligent reader should be able to find all the significant sources in the reference lists of the journal articles cited here.

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[1] CCIR is the Consultative Committee on International Radio and the FCC is the Federal Communications Commission of the U.S.A.

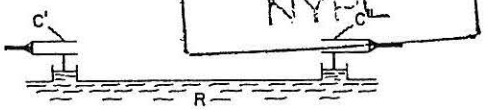


Fig. 1. Tesla's mechanical analogy of "wireless" telegraphy.

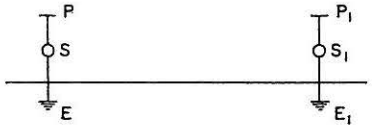


Fig. 2. Tesla's concept of wireless telegraphy (1893).

TESLA THE PROPHET

Some early writings of Nicola Tesla [1], [2] provide some fascinating insight to very recent developments in the field. As is often the case, significant explorations or inventions are often made on the basis of faulty physical concepts or with erroneous initial data. For example, Tesla proposed a mechanical analogy of wireless communication that involved the resonant coupling of tuning forks via pistons to a fluid half-space. This is depicted in Fig. 1. In Tesla's clever analogy, the "sender" excites the tuning fork C' which, in turn, imparts acoustic energy at the same frequency to the fluid within the piston. The resulting disturbance is then propagated through the fluid reservoir R to corresponding piston and coupled tuning fork C'' at the observer. The essential ingredient of the "invention" is that tuned circuits are used at both ends of the path. The misleading aspect of the analogy is that the signal energy propagates entirely through the volume of the reservoir.

The electrical counterpart of the mechanical analogy was illustrated by Tesla in his early patents on wireless communications. An example is shown in Fig. 2 where we have adopted his original notation. In his terminology, E and E_2 are ground "plates" while ESP and $E_1S_1P_1$ are wires connected to elevated sheets P and P_1. Presumably, S is the source generator and S_1 is the detector. Tesla states that "the exact attunement of the two circuits secures great advantage ···."

One might argue that the simple picture shown in Fig. 2 based on Tesla's disclosure in 1893 is the birth of wireless communication. Admittedly, it follows the erudite theoretical and experimental investigations of Hertz who demonstrated the action at a distance from a spark gap discharge [3]. But, by a few years, it precedes Marconi's inventions and practical demonstrations of wireless telegraphy [4].

It seems that both Tesla and Marconi were preoccupied with the role of the earth itself as the medium through which

the useful signal propagated. In fact, Tesla was convinced that the earth itself could be resonated by choosing a frequency that would permit constructive interference from a signal reflected at the antipode after having transversed a two-way path *via the center of the earth*! Tesla became preoccupied with the idea that useful power could be distributed throughout the world from a single transmitting facility. He launched this amazing venture in Long Island in 1899 with the financial backing of J. Pierpont Morgan. In contrast to many of Tesla's earlier investigations, this one was a dismal flop. Marconi's apparent success in 1901 in transmitting a signal from Cornwall across the Atlantic to Newfoundland did not help Tesla's cause. His benefactor withdrew all further funds and nothing further came of Tesla's wireless power project.

EARLY VLF DEVELOPMENTS

The preceding historical sketch provides an interesting backdrop to the development of wireless communications in the present century. Actually, there was a strong emphasis by the early workers on using the long wavelengths for the principal reason that generators for short wavelengths were not sufficiently developed. Also, during the Great War (World War I), the Royal Navy recognized the ability of long electromagnetic waves (i.e., the VLF range) to penetrate sea water to submerged submarines [5]. This presaged an extended development on both sides of the Atlantic on transmitters that could radiate useful signals to global distances. This led to very important discoveries about the properties of the ionosphere that provided a convenient reflector.

More will be said later about the relevant propagation phenomena. But first of all we should indicate how a VLF antenna operates. A grossly oversimplified picture is shown in Fig. 3. The antenna consists of a vertical wire structure excited by a generator at its base. The structure is terminated at the top by a horizontal wire structure that is usually called a "top hat." This is Tesla's "plate." At the bottom, the lower terminal of the generator is connected to a ground system that ideally would be a solid metal sheet extending out to several wavelengths. However, even for the navies of the major powers, only a finite amount of metal is available; for this reason, a system of radial wires is used. The purpose of such a ground system is to reduce the fraction of the total power, supplied by the generator, that is wasted in heating up the earth. In spite of many recent advances in VLF engineering [6], the design of VLF antennas is still more of an art than a deductive science. About the best that can be done is exemplified by the U.S. Navy facility in Cutler Marine that was originally designed to operate at 15 kHz (i.e., a wavelength of 20 km). In this case, the height h of the huge structure is 300 m so that $h/\lambda \cong 0.15$ which is still "electrically small." The ground system consists of copper wire radials with cross bonding that covers an area of 3 or 4 km^2. Even with this tremendous investment, the useful power radiated is only about 1 MW for more than 2 MW to be supplied by the generator. Of course, the situtation was not helped by the fact that ground conductivity in this part of CONUS (Continental U.S. in Navy jargon) is less than 1 mmho/m. Obviously, such a transmitting facility would have worked much better if it were located almost anywhere

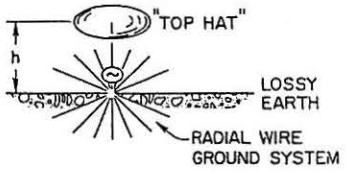


Fig. 3. Classic concept of a VLF antenna.

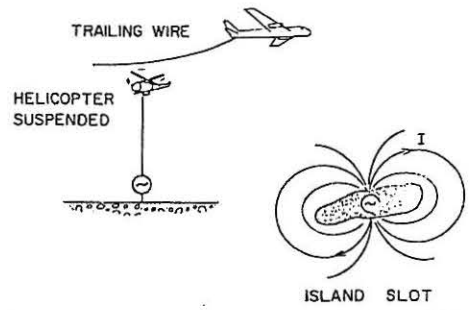


Fig. 4. Various nonconventional suggestions for ELF and VLF radiators.

else. In fact, it is a general property of conventional VLF antennas that their efficiency is improved as any of the following factors are increased: operating frequency, height of the antenna, and ground conductivity.

THE ELF ENIGMA

The possibility that the existing VLF antenna structures can be used to radiate useful signals at ELF is worth examination. The author is aware of several attempts to do this but the results were not encouraging. A rough calculation indicates that the existing Cutler antenna operating at 100 Hz would radiate only 1 W for 200-MW input! Thus we may well ask *is there a better way*?

Several alternative methods to radiate VLF signals have been suggested from time to time [7]. Three such schemes are illustrated in Fig. 4. In the top view, we show a trailing wire behind an aircraft that is presumably excited by a generator whose terminals are connected, respectively, to the trailing wire and the fuselage. Such a system has the advantage that the spurious currents induced in the ground by the near field of the antenna are reduced in a major way. The feasibility of the method, however, is questionable except in very special applications.

Another nonconventional scheme [7] is to find a helicopter and a willing pilot to suspend the top of a base-fed vertical wire radiator. This situation is illustrated in Fig. 4. In principle, the method is attractive since even for VLF the effective height of the antenna can be made an appreciable fraction of the wavelength. Again, except under conditions of dire need, this approach is infeasible.

A third alternative, also indicated in Fig. 4, is to excite an insulating island in a conducting ocean in the manner of a slot antenna. While this is a pretty idea [8] that was proposed for Deception Island in the sub-Antartic, it is really not very promising [9]. Conceptionally, it is really not any better than taking the same horizontal wires and placing them in the middle of a continent with the same ground conductivity. Of

course, the island site allows for an excellent termination of the horizontal wires in the adjacent sea water.

THE BEVERAGE WAVE ANTENNA

While certainly various novel schemes for radiating VLF signals should still be investigated, the attractiveness of such elevated wire configurations shown in Figs. 3 and 4 decreases drastically as the frequency is lowered. However, we do have one early development in antenna technology that should not be overlooked. This is known as the Beverage wave antenna, a name coined after its principal inventor [10]. It is based on the idea that a horizontal wire antenna laid on the ground will indeed radiate by virtue of the finite (i.e., noninfinite) conductivity of the soil. If this is not self-evident, one can think of it operating as a receiving antenna that will be sensitive to the horizontal component of the electric field that is always present when the ground is an imperfect conductor. While the theory of a horizontal electric dipole at the surface of finitely conducting half-space was first proposed by Sommerfeld [11] in 1909, it was Beverage and his colleagues who demonstrated the feasibility of a grounded horizontal wire structure to radiate useful signals in the HF range of the spectrum. For since it was fed at one end and terminated in a suitable matching impedance at the other. The radiation pattern for the vertically polarized fields was essentially end fire in the sense that only weak signals were radiated in the broadside and backward directions.

THE SANGUINE CONCEPT

The idea that a horizontal wire structure laid on the earth's surface could radiate useful signals at VLF and even ELF would seem to be a natural consequence of the development of the Beverage wave antenna. Of course, because the operating wavelength (e.g., 3000 km at 100 Hz) would exceed the length of any contemplated structure, the antenna would hardly act as a traveling-wave structure. Furthermore, there would be no advantage in feeding it at the end rather than the center of the antenna wire. From this writer's viewpoint, this is the genesis of what is now known as Project Sanguine [12], [13]. The earliest version (circa 1960) was called Pangloss when the principal contractor was the Radio Corporation of America, and later it became Sanguine; most recently it has been relabeled Seafarer or sometimes S/S for Sanguine/Seafarer. Some of the early insight into the interesting development of the project was due to the late N. Christofilos [14]. The writer's interest in the theoretical developments was triggered by A. D. Watt who has been a major contributor to the whole subject of both ELF and VLF communications.

In what follows, we would like to give a summary of some principal findings based mainly on what has now appeared in the open journal literature. As mentioned previously, the chronology is not entirely clear but a very useful physical concept emerged in the early 1960's on just how an ELF transmitting antenna does perform. The concept is illustrated in Fig. 5 where the antenna in its simplest version is an insulated

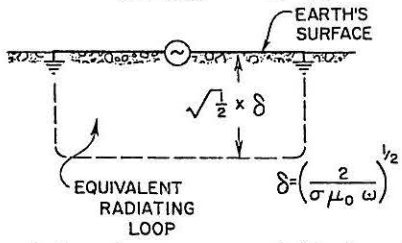


Fig. 5. The equivalence between a grounded horizontal wire antenna and a closed loop.

linear wire on the earth's surface that is terminated or grounded at its end points. With suitable provisions, a uniform current can be maintained over its length for a generator located at any intermediate point. While a rather complicated theory can be applied to predict the resultant field of this structure, it has been found that net effect is equivalent to replacing the linear grounded wire antenna by a closed ungrounded loop of rectangular form that carries the same current. The depth of this rectangular form is numerically equal to $\delta/2^{1/2}$ where δ is the electrical skin depth of the earth for the region of the antenna. Classical theory tells us that $\delta = (\sigma\mu_0\omega/2)^{-1/2}$ where σ is the earth conductivity, μ_0 is the magnetic permeability, and ω is the angular frequency. Typically, δ is of the order of 1 or 2 km for a frequency in the range from 30 to 100 Hz. In fact, δ can be envisaged as the depth extent to which the return current flows. We recognize, of course, that such current is distributed over a volume, but the net effect is as if the current were in the form of a filamental loop.

The postulated equivalent rectangular loop has a radiation pattern, in the horizontal plane, of a figure-eight form with perfect nulls in the broadside direction if everything is symmetrical. Such an observation is also entirely consistent with the full-blown boundary value analysis of a horizontal electric and magnetic dipole located on or just below the surface of a homogeneous conducting earth.

To increase the field produced by the linear wire antenna, we merely increase its length. There comes a point, however, when we run out of available real estate. But even an antenna stretching across a state or province will still be a small fraction of a free space wavelength. Thus, for example, an antenna of length L is equivalent to four parallel antennas of length $L/4$. This simple idea is indicated in Fig. 6. However, grounding rods are needed at the ends of each section.

The next step in the development is to superimpose two such parallel arrays of linear wires at right angles to one another. This is depicted in Fig. 7. Each of these arrays, if fed separately, would have the expected bidirectional or figure-eight radiation pattern in the horizontal plane. However, if the two arrays are superimposed with insulated intersections, the pattern can be steered by suitable phasing. For example, if both arrays are fed with the same phase, the resultant pattern would be bidirectional at an angle of 45° from the axes of the wires. Then if the two arrays were fed in phase quadrature, the resultant pattern would be circular. Of course, many other possibilities exist and many other aspects of the antenna problem [15], [16] are not even mentioned here.

The Electronic Countermeasures Problem for Extremely Low Frequency (ELF) Communications

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Abstract—**An extremely low frequency (ELF) communication system for military purposes needs specialized engineering techniques, in particular signal bandwidth spreading in order to protect against enemy electronic countermeasures (ECM). Qualitative discussion is presented of the processing which the system must have to make jamming difficult, with qualitative discussion of predictive jamming, repeat-back jamming, and high power brute force jamming by adapting electric power systems.**

I. INTRODUCTION

A COMMUNICATION system intended for naval or military use needs some performance characteristics that civilian systems do not need, or, more usually, do not need to the same degree. These are partly environmental: more extreme temperatures, bumpier rides in more rugged vehicles; partly logistic: longer storage, quicker training for lesser skills; and partly operational: protection of the communications system performance from enemy action, including interception of intelligible messages, destruction by physical countermeasures, and communications disruption by electronic countermeasures (ECM). This last is the particular concern of this paper.

Because there are development engineering aspects which are of enhanced importance for naval systems, no technical discussion of extremely low frequency (ELF) communications could reasonably be considered to have covered the range of technical problems unless some mention of these were made. Furthermore, the utility of ELF communication for naval strategic purposes, its only known application, is relatively slight unless there are technically feasible means to maintain satisfactory communications in the presence of ECM to a degree that can reasonably be expected.

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Electronic countermeasures consist either of jamming the system by transmitting noise or interference waveforms at a sufficiently high power level to mask the desired signal at the intended receiver, or else of jamming the system by transmitting a deceptive interference which will be accepted as a signal at the intended receiver, thereby garbling the real messages. Generically, protection against ECM is similar to protection against noise and electromagnetic interference, but there are enough specific differences that a specific discussion is needed.

The object of this paper is to discuss qualitatively the signal processing features which a generic Sanguine system would have for electronic counter-countermeasures (ECCM) and the reasons why enemy responses are difficult. Quantitative discussions are outside the scope of the present work. They are not possible without detailed characteristics of Sanguine equipment and operation and of expectations of hostile ECM. These are too pointed to be public information, and furthermore, can only be done by someone with engineering responsibility in the project. Nonetheless, there is utility to the audience in an ECCM discussion, and the views of an outsider can perhaps be more frankly expressed than can those of better qualified engineers with an on-the-job knowledge of the Sanguine Project. Since the analysis of operation of ELF communication to submerged submarines is presented elsewhere in this special issue [1], [2], attention here will be limited to ECCM features.

With respect to an ELF system like Sanguine, the mission of communicating to submerged submarines on station implies that the link will at times carry high-priority operational messages and will be a high-value

target to an enemy. Therefore, a considerable degree of protection against both physical and electronic countermeasures must be provided. This does not mean that every communication link used by the navy needs to be protected, just as not every naval vessel is fully armored. Furthermore, even for communications systems which fulfill essential operational requirements, it is neither possible nor necessary to provide invulnerable communications, any more than it is to provide unsinkable ships. That is, the degree of protection must be matched to the mission of the communication system, to its technical characteristics, and to the expected range of enemy responses. Even if, in some circumstances, jamming could be successfully accomplished, the communications system is not therefore devoid of all naval value, provided that enemy success requires inordinate expenditure of effort and that alternative means of communication or of operation are provided for. Furthermore, the protection should be compatible with the technical characteristics of the communication link employed; some techniques are essentially concealment measures and need wide bandwidths, burst transmissions, narrow beamwidths, etc., and are therefore incompatible with lower frequency radio systems. This is not a relevant objection to an ELF system provided that a satisfactory suit of ECM techniques can be found to meet the mission requirements, just as the fact that a battleship did not have the same set of good characteristics as a motor torpedo boat did not mean that the battleship was poorly designed for its own mission.

These naval system considerations sketch requirements and tradeoffs which the communications engineer must then make more explicit and find engineering techniques to meet. Furthermore, because recent discussion of technical aspects of defense issues has often assumed that only systems engineered to be invulnerable have any military value, it is appropriate to state explicitly the need for a point of view which balances costs and benefits in engineering ECCM protection for a naval communications system. Naturally, it is still possible for reasonable men to differ on the degree of protection which is necessary or desirable and on the amount of protection actually provided by the ECCM techniques which are used.

For all digital communication systems, the user's primary requirements are in terms of data transfer rates, message delays, and the frequency and distribution of errors. Once a modulation system has been chosen to meet the data transfer and delay requirements, the error probability relationship fixes the signal-to-noise ratio needed at the receiver to reduce the error rate to the required rate. The received signal-to-noise ratio can then be obtained by trading off transmitter power, antenna gains, propagation loss, etc. The significant point, for the military problem, is that the ECM task is to increase the noise level perceived at the receiver by means of the jamming transmitter, antenna, propagation path, and jamming waveform. The jammer will attempt to exploit system vulnerability by using special waveforms or special timing of its waveforms. The ECCM design will attempt to eliminate special vulnerabilities and to strengthen the system against straightforward high power (alias brute force) jamming.

For the ELF application, transmitter power is expensive. Enough must be provided for successful transmission to the operational areas in the natural noise environment, but it is not economically reasonable to rely on increases in power as the major ECCM feature. The ECCM potential of the antenna patterns are similarly severely limited. The transmitting antenna is expensive because of being physically long. The natural figure eight pattern of each separate element is well suited to broadcast coverage of the operational areas, and extra directivity is not practical to achieve. The receiving antenna configuration is constrained to be compatible with submarine operations and therefore is also limited in directivity. Of course, it is not easy for an enemy to build transmitters and antennas either, but since there is no special advantage to the Sanguine system, the main ECCM reliance must be elsewhere, namely on spectral spreading of the transmitted bandwidth.

II. SPREAD SPECTRUM

The basic principle of spectral spreading is to occupy much more bandwidth or a much longer time duration, or both, than is needed to transfer the message. This follows from the basic principle of signal detection theory: for binary transmission of known signal form in white Gaussian noise, the error probability depends only on the signal-to-noise ratio, which can be expressed as signal energy per bit divided by noise spectral density, and therefore is independent of the waveform and bandwidth actually used for transmission. Naturally, the applicability of this idealized form always requires examination, and may require modification in particular cases, but it serves as a useful and meaningful starting place.

The signal transmission is either dispersed throughout the time-bandwidth region in such a way that the desired receiver can reassemble the message, or is separated into short pieces which occupy scattered parts of the time-bandwidth region which the desired receiver knows in advance. The jammer, who does not know the dispersing rule or scattering rule, must fill each element of the whole time-bandwidth space occupied by the transmission with jamming power to be sure of effective jamming, and therefore the ECCM processing gain is the ratio of time-bandwidth products, that of the actual transmitted signal to that of the minimum needed to carry the message signal. ECCM processing gains of 20 or 30 dB can often be achieved by these means. However, the ideal improvement must be diminished by processing losses from the receiver implementation or channel distortion, and the spreading rule must be noncircumventable by the jammer. The difficulty of the ECCM problem is in finding means to realize the spreading which do not make excessive demands on the stability of the communication channel, which do not usurp or pollute too much of the spectrum,

which are practical and reasonably convenient and inexpensive, and which cannot be circumvented by the jammer. Attempting to meet all these requirements satisfactorily in a particular application is where the complexity of the system design occurs.

For Sanguine, the amount of bandwidth spreading is not currently constrained by international regulation of the radio spectrum or by compatibility with other users, since there are none, but rather by limitations of the transmitter and antenna or of the equalizing in the receiver to compensate for the filtering of the ELF signal with transmission through the sea. The time duration is limited by the requirements on message-delivery time. However, the amount of spreading which can be easily realized, 10 or more Hz for a transmission bandwidth, say, is much in excess of the minimum required to send the critical messages, and therefore a substantial amount of processing gain can be realized, about 20 dB or more overall. Spectral spreading will be best accomplished by direct sequence spreading, i.e., Boolean adding a binary sequence from a pseudorandom sequence generator clocking at the transmission data rate to the message sequence clocking at the message rate. The sum is a binary sequence at the transmission rate which can be used as the input to the modulator, and is eminently suitable for a coherent continuous phase frequency-shift-keyed (FSK) transmission such as Sanguine. If the receiver estimates the transmission sequence correctly, Boolean addition with a synchronized replicating sequence generator clocking at the transmission rate will regenerate the message sequence at the message rate.

The direct sequence spreading disperses the transmitted waveform throughout the time-bandwidth region occupied, although the RF spectrum of minimum shift FSK (MFSK), is not white across the occupied band, and therefore the transmission is not spread with maximal effectiveness. The alternative of scattered transmissions in parts of the time-bandwidth region, which corresponds to frequency hopping or burst transmission, is not suitable for ELF because it involves discontinuous waveforms which are unnecessarily awkward for the ELF transmitter to handle when an equally effective continuous alternative is available.

In order for the spreading to be effective, the jammer must be unable to predict the future of the transmitted sequence because, if he could, he could arrange for the jamming waveform to follow the same spreading sequence as the signal, whereupon the receiver after despreading would still find the jammer present at full strength. Therefore, the spreading sequence must be pseudorandom and not predictable. These are the same sort of requirements as for cryptographic generators, and the enemy effort which might be devoted to learning to predict the Sanguine spreading sequence is of the same size as might be given to attempting to break a cipher. Therefore, it may be simplest to use cipher sequence generators, if appropriate models can be made available, or if necessary, to develop special purpose spreading generators using the principles of cipher sequence generators. Under these circumstances, the Sanguine spreading sequence can be made as secure from enemy prediction as the Sanguine message is from enemy decipherment.

Even without the possibility of prediction, the jammer can attempt to make straightforward spreading ineffective by pulsing his jamming power during the duration of one or several message bits to permit the unhindered transmission of nearly all the message in order to drastically reduce the signal-to-noise and jamming ratio on a few bits to be sure to cause a few errors. The error rate requirement on digital communications is usually quite strict, no more than one error in 10^4 or 10^6 bits, for example; and critical operational messages may be required to be error free, as a fail-safe measure. Therefore, occasional bit errors can be an unacceptable degradation to the system, and so a worthwhile objective for the jammer. This jammer tactic is difficult to use at ELF because pulsed operation is difficult, but it is so effective against an unprotected system that it would be prudent for Sanguine to repeat the message several times, which, of course, reduces the spectral spreading of each separate repetition, but leaves the overall time-bandwidth expansion unchanged, and to pseudorandomly shuffle the bit sequence independently in each message repetition. Then a jammer who pulses in time without knowledge of the pseudorandom shuffling sequence cannot count on hitting all of a single message bit, but only on hitting one of several copies on each of several message bits. The Sanguine receiver will then be able to reconstruct the message by ignoring or de-emphasizing the noisy copies. In fact, the message repetitions correspond to introducing time diversity into the Sanguine transmission, and the time-varying pulsed jamming gives different signal-to-noise ratios on the different diversity branches, so that the Sanguine receiver overcomes the pulsed jammer threat at the cost of the additional task of diversity combining in a nonfading channel.

It is noteworthy that the spectral spreading is directly of value in estimating the signal-to-noise ratio on each diversity branch, since the power in the spread bandwidth is the signal plus noise and jamming power, while the power in the narrow bandwidth after despreading is the signal only. (The noise and jamming will not despread, but some of their power will lie in the narrow bandwidth, biasing the signal estimate.) The choice of diversity combining algorithms and of averaging times for the branch signal-to-noise ratio estimates is the detailed design task. The jamming interference can be deliberately variable, and therefore the diversity processing must be examined to be sure that it does not itself add extra vulnerability to jamming.

The analogous aspect of frequency-hopping ECCM systems is perhaps more familiar. If the jammer ignores the frequency hopping and jams one elemental frequency interval, then when the transmission finally hops to the jammer frequency, a bit will be jammed. The antidote is to use multiple hopping with frequency or time diversity.

Look-ahead interference avoidance is a valuable alternative to avoid natural or inadvertent interference from disinterested users of the band, but difficult to implement effectively against deliberate jamming which may hop enough not to be predictable.

A further benefit of spectral spreading is a much reduced sensitivity to the jamming waveform. The division of the signal energy used to convey a single message bit into a number of distinct transmission elements sent in several noncontiguous groups means that the receiver decision on what the message bit is, is based on the sum of a moderately large number of separately processed received waveform elements. These are substantially the conditions that the central limit theorem of probability requires, and therefore the noise and jamming are effectively Gaussianized by the despreading process, whatever their original waveshape may have been. This helps to insure that the performance predictions are realizable.

The waveform of a single transmission element, for example, either 3½ cycles of a 70-Hz wave or 4 cycles of an 80-Hz wave, both from zero to zero, will have a spectral shape across the band. Since this is not uniform, a narrow band jammer in the middle of the band, for example, a sine-wave jammer, will be more effective than broadband noise of the same inband power by the ratio of jammer spectrum times signal spectrum averaged over the band divided by signal spectrum averaged over the band. Some moderate loss to an optimized spectrum jammer should be accepted, 1–2 dB, say. Exceptional vulnerabilities or vulnerabilities to exceptionally common waveforms can be protected against if necessary, thus; for example, the receiver can have a tunable sine wave rejection filter included at a proper place in its front-end processing. Since at ELF the receiver processing can be performed by digital computation, the basic limitation on the filter rejection is that it be narrow enough not to interfere seriously with signal reception and wide enough not to be critical to position. This type of addendum to spread-spectrum operation should be optional, if included at all, since the extra complexity of operation is not worthwhile unless substantial benefit is gained thereby.

With a well designed spread-spectrum system, the jammer is denied equal accessibility to the Sanguine receiver's bit decision point by simple waveforms and cannot predict in real time what jamming waveform will be fully effective. Repeat-back jamming is made much more difficult because the repeater time delay must be small compared to a transmission element which is much shorter than the time duration of a message bit. The enemy may then be limited to high power brute force ECM or to physical countermeasures against the Sanguine transmitter, receiver, or propagation path.

III. HIGH POWER (BRUTE FORCE) JAMMING

Since waveform prediction is denied, and repeat-back jamming is difficult, expensive, and unreliable, the best form of ECM may be the use of enough jamming power to overwhelm the Sanguine signal regardless of the need to overcome the spectral spreading. The jamming transmitter is best located on land over ground of low conductivity, just as is the Sanguine transmitter. To reduce the range from jammer to receiver substantially requires locating the transmitter aboard ship with the antenna trailing in the sea, but the loss in radiation effectiveness because of the high conductivity of sea water overwhelms the gain from reduction in range. As a result the path loss from land-based jammer to receiver is not very different from the path loss on the desired Sanguine path, so that the radiated jammer power must be several orders of magnitude larger in order to overwhelm the spreading advantage. As the basic equation for Sanguine field strength shows, this depends on the square of the product of antenna current and antenna length, and therefore can take whatever economic advantage is possible in using more of one factor then another.

A special purpose jamming transmitter would therefore need to be much larger than the Sanguine transmitter. The jammer can presumably be a soft system and therefore can save money by not burying the antenna cable nor distributing the transmitter. However, although the cost per radiated watt can be less for the jammer, the total jammer cost should be substantially more, since much more radiated power must be provided.

At ELF, the higher cost of a specialized jamming transmitter does not complete the discussion, because an electric power system can be adapted to serve as an ELF transmitter. Since the cost of the basic facility is already assumed for its normal power utility purposes, only the marginal cost of adapting to the jamming mission can fairly be imputed. An adaptation study is a sizable engineering task in itself and only a brief sketch of things to take into account will be given here.

An electric power system ordinarily operates at 50 or 60 Hz, three phase, balanced, with high-voltage transmission lines feeding a relatively high load impedance. Some modern transmission lines are dc lines operating at high voltage with rectifier-invertors at each end. An ELF transmitter for Sanguine needs to operate at a different frequency, single phase, unbalanced, with a low impedance load at the remote end of the transmission line. The task of adapting from one mode of operation to the other is reasonable but not trivial.

Power transmission lines are operated current limited at high voltages as the most economical design. Therefore, when the far end of the line is grounded in order to provide the ELF antenna, the current cannot be substantially increased without damaging the line, so that the line voltage must be reduced. As a result, the power-handling capability of the line as an ELF antenna is substantially less than for its normal use, essentially by the ratio of the sum of station grounding impedances and earth return impedance to the normal load impedance. The far end of the transmission line must be grounded, presumably by connecting to the station ground at the far end terminal. For normal operation, the station ground will support much larger fault currents while maintaining

safe potential differences in the terminal and its environs. It is possible that the series resistance of the earthing arrangement is higher than necessary, which is irrelevant to normal operation, but seriously objectionable in the Sanguine system transmitter, where it represents wasted transmitter power. For the Sanguine jammer, however, the series impedance of station ground to earth is again irrelevant since there is more power available than the jammer can use, and the series impedance does not affect the transmission line current which is the significant factor.

Ordinarily the station grounding system is carrying current only for short times during fault conditions, but throughout ELF jamming operation, it is necessarily part of the normal load circuit. This should be tolerable, since the current is the normal load current and the required connection to ground is from the step-down transformer at the end of the transmission line and therefore can be kept somewhat isolated from the rest of the terminal.

The sending end of an ac line must be adapted by a separate lower voltage transformer, or an extra tap added on the normal transformer. Also, the generator should continue to operate three phase, with one phase driving the grounded transmission line and the other two phases adapted to terminate in loads of the same impedance. It may be possible to open-circuit two phases since the transmission line is operating at much reduced power; electrical unbalance in the generator at reduced power may not be large enough to be harmful. The single phase which drives the transmission line can be connected to one conductor only, as in normal operation, which reduces the operating power still further. It can, adapted by further switching at the sending terminal, use all three conductors to carry the single phase current, putting the full current capability of the line, at reduced power, in use for jamming.

Adapting the power system to the Sanguine frequency is a substantial problem. The turbines and generators are optimized for operation at the normal power frequencies and a reasonable tolerance interval around it. It would therefore be prudent for the Sanguine system to select a transmitter frequency outside the normal range. Then it will not be reasonable with modern tight-tolerance designs, to operate steam or gas turbine generators outside the normal range. Hydroelectric generators are slower speed multipole machines which can be adapted to generate the Sanguine frequency by a combination of changing speed and changing the number of poles on the machine. The additional switching and modifications to the rotating elements are comparatively minor changes, but not trivial.

When a dc transmission line is available, another option is possible. The recifiers at the sending end are ordinarily controlled to convert the three-phase power frequency input to dc, but the control voltages can be adapted by reprogramming to be a very crude cycloconverter, converting the input to a single phase ac at the Sanguine frequency. No extra power-handling equipment is required. Without it, the converted wayeform is rough, and a moderate unbalance is reflected back to the generator but since the transmission line is operating at reduced power, the generating system should be able to tolerate the unbalance. This form of cycloconverter-operation would certainly not be satisfactory for normal use, because of both lowered efficiency and increased electromagnetic pollution, but for occasional high-priority jamming it is likely to be acceptable.

The semiconductor devices which are installed as the best choice for conversion to dc may not be the most suitable for cycloconverter operation and may limit the amount of design freedom to reprogram commutation of the rectifiers. Furthermore, the necessity of observing the peak current limits of the devices under the reprogrammed switching necessary for cycloconversion to the Sanguine frequency may reduce both the peak line current and, even more, the component of line current at the Sanguine frequency to values well below the current capacity of the line in normal operation. In addition, operation of the dc transmission line to carry ac at the Sanguine frequency necessitates re-examination of the insulation and corona characteristics; however, since the line will be operating at much reduced voltage and power, ac operation is likely to prove satisfactory without modification of the installed equipment or normal maintenance procedures.

New converter stations can be designed for dual purpose operation at economic penalities if higher cost semiconductor devices are used. The design problem for cycloconversion from the power frequency to so close a frequency as Sanguine is likely to use, 75 Hz, say, is insoluble with normal requirements on efficiency, waveform purity, and cost, but since the jamming mode needs much less power, crude cycloconversion can be accomplished. A better alternate may be to reconfigure the normal converter equipment into two parts using one half as a converter supplying dc to the other half which inverts to the Sanguine frequency. This is likely to be too drastic an adaptation to be economical for already installed converter terminals.

The part of the power system which is given over to Sanguine jamming must be disconnected from the normal power system for the duration of its mission. Furthermore, power transmission lines which are to be adapted for ELF jamming need to be well oriented with respect to the operational areas to be jammed and located over ground of low conductivity, neither condition being necessary to their normal functioning.

Furthermore, operation of large transmission lines unbalanced to ground will cause local induced voltages, an aggravated problem as compared to the Sanguine transmitter because of both the higher current and longer length of the adapted power transmission lines. Then it may not be reasonable to jam freely at ordinary times; but at truly crucial times, the inconvenience and potential danger to nearby people and animals will likely be considered acceptable. The costs of mitigation of the local interference would do much to eliminate the economic advantage of using existing power facilities, although if the

line passes through sparsely settled country without metallic structures near the line, fences, pipelines, communications lines, for example, the mitigation costs can be much reduced.

When a large part of an electric power grid system is available, one can contemplate an alternative antenna configuration. The ordinary ELF antenna is a vertical current loop formed by the physical transmission line and the earth return effectively about a skin depth below the surface, but with a transmission grid available, it may be possible to form a horizontal current loop with a very much larger area by selecting a chain of transmission lines in the power grid which form a closed loop, and adapting them all for unbalanced operation.

In adapting parts of the electric power system for ELF jamming, the ELF power must be much larger than Sanguine to overcome the spectral spreading and an increase in ground conductivity or improper orientation. Furthermore, the electric power capability of the jamming part is much larger again than its ELF jamming power capability. On the other hand, the marginal cost, per electric power watt, of adapting to ELF jamming is very much less than acquisition cost for a special purpose jamming system. It is likely, however, that the net balance leaves the enemy investment in power system adapting equipment considerably higher than the investment in Sanguine transmitter equipment. Furthermore, the Sanguine receivers can use sine-wave traps to reject power system jamming, if necessary, as mentioned in Section V, and the costs of adapting the power system to more complicated waveforms are much greater.

IV. REPEAT-BACK JAMMING

The applicability of repeat-back jamming depends on intercepting the Sanguine transmission, transmitting the intercept to the jamming transmitter, and emitting the jamming signal. The use of bandwidth spreading shortens the duration of each transmitted elemental waveform and correspondingly shortens the delay time at which the relay through the jammer becomes too late to match the Sanguine transmission. For example, if the transmission had been spread to send ten transmission bits /s and half the bit is to be jammed, the delay along the repeat-back relay path must be kept to 50 ms or less, which is really a very short time in which to do all the necessary parts of the repeat-back job. Not all the repeat delay time can be allocated to propagation delay, since reception and processing of the intercept, and buildup time of the jamming transmission add delays at the jammer terminals which are substantial fractions of the duration of a Sanguine transmission element. The intercept must collect a moderate piece of a Sanguine elemental waveform in order to identify which of the two possibilities it is in its noise background and then must transmit toward the jamming transmitter. The jamming transmitter must generate a waveform with the same general character. The jammer will not begin to be effective until after the rise time response delay of both jammer transmitter and [illegible] jammed, and the Sanguine receiver can use programmed automatic gain control (AGC) or blanking within the bit time, if necessary.

Despite the enemy investment in intercept, relay, and repeat capability, he cannot be sure of being effective, if Sanguine has antirepeater ECCM processing options on line or available. One should not ignore the fact that the addition of a number of ECCM options, one of which must be correctly selected in real time, adds to the operational difficulty of Sanguine reception, but this is too small a return on the ECM investment to be by itself satisfactory.

To continue the same example, if 20 ms is used up for delays internal to the intercept terminal and jamming transmitter, 30 ms are available for excess propagation delay, which corresponds to 6000-km excess path length by way of the repeater compared to the direct path, immediately ruling out the use of geostationary satellites. A low altitude satellite will only be able to receive a signal while near the Sanguine transmitter, so that a number of them would be required, with a consequent large expense. Aircraft intercept over the transmitter, or surface-based clandestine intercept are not easy to do, and must still find a communication means to relay the intercept to the jamming transmitter which is reliable during the time that it is needed. An intercept in the submarine operational areas or in jammer-controlled territory will be able to receive an ELF waveform in the Sanguine bandwidth and relay information to the jamming transmitter, but the received waveform will be almost all irrelevant noise and the intercept receiver will need to do real time extraction of the transmission bit sequence of the Sanguine transmissions, a task much harder than that which a Sanguine receiver does. The jamming transmitter will need to switch on and off, so that the intercept receiver can look through to see only the Sanguine transmission and noise. The Sanguine receiver can correlate many transmission bits before making a tentative decision for input to further decoding, but the intercept receiver must make a hard decision on each transmission bit. The signal-to-noise ratio at this point is so low and consequently the error rate is so high that the nominal ECM repeater may be effectively a noise jammer.

The jamming repeater will only be effective when the phase of the jamming transmission is opposed, at least in part, to the Sanguine transmission. Thus maximal effectiveness of the jamming is limited to a portion of the operational area. Furthermore, the Sanguine receiver can incorporate protective features against repeater jamming; for example, by an adaptation of the leading edge tracking technique used in radar.

Neither brute force nor repeater jamming are impossible, but both will be very burdensome and very expensive to the jammer.

V. FEASIBILITY OF AUXILIARY PROCESSING

In addition to the spread spectrum processing and specific ECCM elements, discussed very summarily above, [illegible]

functions which have more or stricter requirements because of the need for good antijamming performance. Furthermore, since the transmitting subsystem is so expensive and the propagation is stable, it is important to keep processing losses in the receiver small. Therefore, it is necessary to check that the auxiliary processing which a receiver must do remains feasible under Sanguine conditions.

First is the need for a local time reference in order to keep the local despreading sequence in step with the received sequence. This will be derived by adjustment with respect to the received sequence and from stable clocks on board the submarine. For ten transmission bits a second, the time should be kept accurate to about 1 ms, which is quite reasonable.

The low input signal-to-noise ratio per transmission bit implies that phase coherent reception has several dB advantage over noncoherent reception, and the communication channel is stable enough under natural conditions that coherent reception is feasible. The phase estimate which the receiver uses must be formed by long time integration, extending about ten times longer than the duration of a coded bit, and therefore provides an independent phase estimate every few tens of seconds, if the coded bit rate is one bit per second or less. This is sufficiently fast to track natural ionospheric height changes. Nuclear explosions can also cause significant phase changes if they are large enough, and close enough to the propagation path, and acting on a not yet unduly disturbed ionosphere. Both the physics and the scenarios for the nuclear effects are outside the scope of the present paper. We recognize that some types of multiple bursts will severely disturb some paths, and that some protection can be afforded to Sanguine reception by more elaborate phase estimation or a change to noncoherent reception and do not claim to have resolved this aspect of the problem.

The best form of reception involves probability estimates of the message conditional on the received waveform, and therefore on the amplitude of the received signal and noise. For convenience much of the processing should be done digitally, so that there is a quantizing loss involved in the analog-to-digital conversion, and in errors in noise normalizing, which involves proper setting of the receiver AGC. Previous studies of coding have shown that three- or four-bit quantizing will keep the loss to a few tenths of a dB for signals in Gaussian noise, and the spreading and interleaving, combined with the noise clipping processing, have the effect of Gaussianizing the received ELF noise. The tolerable quantizing grain is sufficiently coarse that the necessary AGC quality can be readily realized.

The processing actions described above follow action of the front end of the ELF receiver. The receiving antenna will be two electrodes spaced along a cable streamed behind the submarine which helps to eliminate flow noise and locally generated noise aboard the submarine. The atmospheric noise which is received at ELF is very impulsive and therefore its deleterious effects can be much reduced by clipping the noise peaks. Successful operation for noise reduction involves several factors: the receiver bandwidth must be wide enough not to round off the noise peaks, but not so wide as to let in a significant amount of receiver noise; the noise clipper must work accurately, and subsequent filtering to narrow the receiver bandwidth to that of the Sanguine transmission must reject out-of-band noise and not distort the signal. Sine wave traps or other special waveform rejection filters should be inserted here after the noise clipper, so that the noise reduction will be unaffected by their presence. The trap filters then process the received signals in the spread transmission bandwidth and send their output to the despread processor for compression to the message bandwidth. The effective bandwidth of the trap filter is sufficiently less than that of the Sanguine transmission bandwidth that the signal distortion caused by the filter is tolerable. For submerged reception, a further complication arises because the transmission path from the sea surface to the submerged antenna is dispersive, so that the sharp atmospheric noise peaks are smeared out. The transmission characteristic of the ocean is precisely known as a function of depth, so that the Sanguine receiver can equalize the received waveform before clipping to maximize the effectiveness of the noise reduction processing.

The feasibility of reducing the effective noise level substantially by well designed nonlinear processing seems assured, given the measured atmospheric noise and the Navy's values for submarine noise levels, antenna performance, and depth compensation capability.

The preceding auxiliary processing functions of the Sanguine receiver are feasible for the values of input signal-to-noise ratio required to receive the message with a low enough error rate. Furthermore, none of the auxiliary functions appear to offer the jammer a new vulnerability easier than directly corrupting the transmitted data.

VI. CONCLUDING REMARKS

This essay has relied on other papers of the ELF special issue for exposition of the basic operation of Sanguine and has limited itself narrowly to ECM and ECCM considerations. Even for these, only generic discussion has been given, partly because there is no need to rederive standard signal in noise theorems just because the noise is jamming, and partly because the author has no responsibility for, nor influence on, any aspect of the actual Sanguine development effort. It seems, nonetheless that there is a value to a paper which concentrates only on the ECCM aspects of the Sanguine problem, assuming an audience skilled in modern digital communications.

In general, enough desirable antijamming features can be incorporated into the Sanguine system to make the jamming task severely onerous. These do not degrade the other operational aspects of a Sanguine system which the Navy is prepared to accept. No system, including this one, can be made immune to indefinitely large jamming power or indefinitely big and frequent disturbances of the

Propagation Measurements in the Extremely Low Frequency (ELF) Band

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Abstract—An experimental measurement program has been conducted to determine propagation parameters in the 40–50 and 70–80 Hz ranges. These measurements have utilized a transmitter in Wisconsin radiating a sinusoidal signal at radiated power levels of 0.5 W at 45 Hz and 1 W at 75 Hz. Sites have been located at Nova Scotia, California, Utah, Hawaii, Norway, Greenland, Greece, and Saipan. Using sites on the same great circle path as the transmitter, it has been possible to estimate *average* attenuation rates and excitation factors with high accuracy subject to the constraints discussed in the paper. Both daytime and nighttime attenuation rates and excitation factors are discussed.

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INTRODUCTION

ONE OF THE elements having a major impact in the sizing of an extremely low frequency (ELF) communications system is the propagation channel. Ideally, one would like to collect reasonable received signal statistics for sites over the proposed communication range. However, lacking a transmitter of sufficient radiated power to perform such experiments we can only perform a set of less than optimal measurements at somewhat closer ranges. In particular, since the earth's surface and lower "edge" of the ionosphere effectively form a waveguide, we can measure some suitably defined average

mode propagation parameters. With knowledge of these parameters we can then make reasonable field strength predictions at more distant receiver locations.

As a result of optimization studies it was decided to concentrate on the band 40–80 Hz. Simply stated the frequencies above 80 Hz were ruled out for reasons of high attenuation rate (both in the ionosphere and in sea water) and below 40 Hz by rapidly increasing antenna size and decreasing signaling bandwidth. Since the proposed communication bandwidths were of the order of 10 Hz it was decided to examine in detail the bandwidths 40–50 Hz and 70–80 Hz thereby avoiding interference from the 60-Hz power lines. A large number of theoretical calculations have been performed in this frequency band over the past fifteen years principally by Wait [1], [11], Galejs [2], and Jones [3]. Out of necessity their solutions employ idealized models of the conductivity profiles for the D and E regions of the ionosphere and hence the accuracy is limited by the considerable uncertainties associated with these profiles.

Sferics (the electromagnetic radiations from lightening strokes) have commonly been used as energy sources and consequently a number of estimates of the attenuation rate have been made by the comparison of signals from two or more receiving stations. Unfortunately, the spread in estimates of attenuation rate as measured with sferics has been particularly large, due primarily to the large number of uncertainties inherent in this technique. It must be realized, for example, that even an uncertainty in the attenuation rate α of 0.1 dB/Mm when extrapolated over distances of 10 Mm makes considerable cost difference in additional required transmitter power. The spread in values of α (theoretically calculated or measured from sferics) was much too large to be used in an intelligent sizing of a communications system. For example, at 45 Hz under daytime conditions, estimates range from 0.5 dB/Mm to more than 2.3 dB/Mm. It became obvious that a series of measurements with a controlled source were necessary in an attempt to resolve the large uncertainties.

Far field measurements in this frequency band from a controlled source (transmitter) have been limited due to the difficulty of generating significant amounts of radiated power with a reasonable cost antenna system. Until the current series of measurements only Ginsberg *et al.* [4] in 1966–1967 had performed measurements with a transmitter source. For their CW transmissions at 78 Hz, a single horizontal (176 km) wire strung on poles in North Carolina served as a transmitter antenna. The propagation path extended to Iceland for a total distance of 4.9 Mm.

By 1971 sufficient power was available from the Wisconsin Test Facility (WTF) and consequently a series of tests were undertaken. The transmitter antenna system consists of two orthogonal horizontal dipoles individually center fed with ends grounded. The length of each antenna is 22.5 km, being simply a single wire transmission line hung on telephone poles. The current in each antenna is limited to 300 A and by selecting different phases between

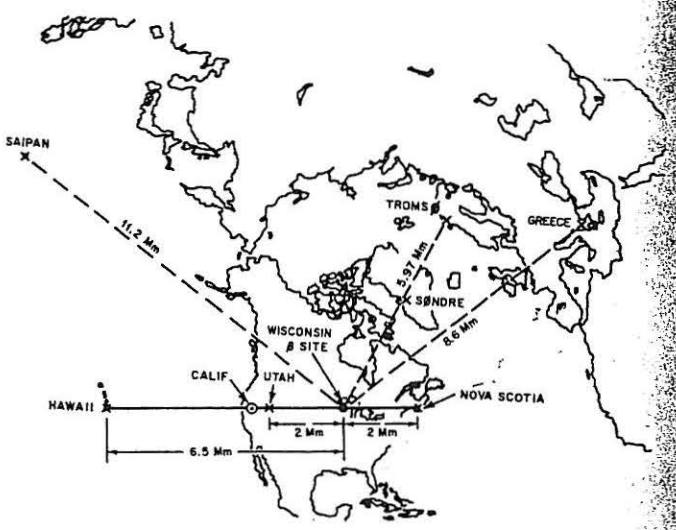


Fig. 1. Receiver site locations.

the line currents the antenna pattern can be steered. The dominant feature of the experiment is that the maximum radiated power is about 0.5 W at 45 Hz and 1 W at 75 Hz but even with these low radiated powers we have performed meaningful propagation measurements as far away as Saipan (d = 11.2 Mm). Fig. 1 shows the locations of the Lincoln Laboratory receiver sites, and Table I lists the experimental periods.

As a consequence of the large expense associated with simultaneously operating the WTF transmitter and a number of remote receiver sites, operating time has been limited to several weeks per year. The problem was to select a series of measurements which enables one to size a communications system with a high degree of confidence. It would be very advantageous to be able to predict received signal strengths with as few parameters as possible (i.e., an attenuation rate α and an excitation factor E). That this might be feasible was suggested by the character of the received signal during the first few tests as follows.

1) As long as the direct path between the transmitter and receiver was entirely under daytime conditions (or entirely under nighttime conditions) the signal level remains essentially stable over a several hour period. The variations seen in the signal estimates could largely be ascribed to the noise background. No large amplitude fades were observed.

2) The effect of the sunrise or sunset terminator intersecting the direct path results in a relatively smooth transition from day to night conditions.

3) The received signal phase changes rapidly during sunset or sunrise transition periods (of the order of tens of degrees over a few hours) but changes only several degrees during the time period when the direct path is under uniform conditions.

Accordingly, the first three series of tests were set up specifically to measure the *average* propagation parameters, namely α and E. Transmission periods were selected so that the propagation path was either entirely under d-

TABLE I
LINCOLN LABORATORY MEASUREMENT PROGRAM

Period	Transmission Hours/Day	Frequency Interval	Site Locations	Report of Results
July 6–24, 1970	4 h during day 4 h during night	45, 75 Hz	Hat Creek, Calif. Hawaii	(7)
Mar. 15–Apr. 9, 1971	8 h during day 8 h during night	Odd frequencies from 41–49 and 71–79 Hz	Wendover, Utah Hawaii Nova Scotia	(8)
Oct. 13–Nov. 4, 1971	8 h during day 8 h during night	Odd frequencies from 41–49 and 71–79 Hz	Wendover, Utah Sondre, Greenland Tromsø, Norway Maine: USC–NLL[a]	(5)
May 1–19, 1972	24 h day	Odd frequencies from 41–49 and 71–79 Hz	Tromsø, Norway Greece Saipan Alaska Greenland USC–NLL	(6)

[a] Underwater Systems Center, New London Laboratory.

time or nighttime conditions. The periods of transition were carefully avoided. The calculation of the daytime values (α_D, E_D) or nighttime values (α_N, E_N) then resulted from an appropriate averaging of each site's received signal strength over a matter of several tens of hours and over a specified frequency band. These averages were necessary to reduce the effects of both the low single estimate signal to noise ratio and the global standing wave pattern. The results of these tests were valuable in preliminary performance predictions for arbitrarily located receiver sites.

The main purpose of the last series of tests was to collect signal statistics on the WTF transmissions over a reasonable period of time at a number of remote sites (Greece, Norway, and Saipan). Accordingly, WTF transmitted a CW signal for the entire 24 h period, switching frequency every few days.

About 3140 h of ELF data have been recorded at Lincoln's receiver sites and *all* these data have been processed at least once for the signal and noise estimates. The estimates were spaced every 1.42 h at most. These raw samples were in turn processed (according to the techniques to be described) before the propagation parameters could be computed. The distillation of this huge amount of data into a simple propagation model characterized by two average propagation parameters in a way seems too idealized. However, with these two propagation parameters we have been able to predict field strengths at other remote sites and generally the ensuing average measurements are only about 1 dB in error from predictions.

These tests have developed a considerable data base which can only be abstracted in a paper of this size. The curves shown are only representative of the large number available elsewhere [5]–[8].

We devote a considerable portion of the report to a description of the data collection and analysis so that the precision required for making meaningful α and E measurements can be appreciated. Precision measurements on α and E are, of course, an absolute necessity if these values are to be utilized in the performance predictions of an ELF communications system.

PROPAGATION THEORY

The general behavior of ELF propagation in the earth–ionosphere duct has been subjected to intensive theoretical analyses over the last 15 years and most of the scientific community is in reasonable agreement on the principal results. One simple model (referred to hereafter as the Wait model) simply replaces the ionosphere with an equivalent isotropic uniformly stratified ionosphere that is characterized by an effective surface impedance at a fixed effective height h. Succeedingly more complex ionospheric models have been utilized in an attempt to obtain propagation parameters that reflect a more reasonable representation of the ionosphere. For example, more detailed computations have divided the ionosphere into concentric finely divided shells with radial or tangential ambient magnetic fields representing the earth's magnetic field. Galejs in a recent excellent text [2] catalogs a large number of such computations. It should be pointed out that virtually all the analytical and numerical solutions have employed ionospheric models with no azimuthal (horizontal) variations. As such, the propagation behavior through transitions such as the day–night terminator has been largely ignored.

For the Wait model of the ionosphere, the "direct" component of the far fields generated by a single horizontal antenna at the earth's surface can be accurately represented by the asymptotic formula

$$(H_\phi)_D \simeq \frac{IL\cos\phi}{\eta}\left(\frac{\pi\mu_0}{2c}\right)^{1/2}\left\{\frac{1}{h[\sigma_e(c/v_{ph})]^{1/2}}\right\} \cdot\left\{\frac{1}{d^{1/2}}\left(\frac{(d/r_d)}{\sin(d/r_e)}\right)^{1/2}\right\}\exp\left[-(\alpha' d) + j\left(\omega t - k_0\frac{c}{v_{ph}}d + \pi/4\right)\right] \quad (1)$$

and

$$(E_r)_D \simeq -\eta\left(\frac{c}{v_{ph}}\right)(H_\phi)_D \quad (2)$$

where

η	120π;
μ_0	$4\pi \times 10^{-7}$;
c	velocity of light in free space;
ω	$2\pi f$;
σ_e	ground conductivity beneath the antenna;
r_e	earth's radius;
IL	current moment of transmitter;
ϕ	angle between axis of horizontal antenna and propagation path direction;
d	short great circle distance between receiver and transmitter $d \lesssim \pi r_e$;
h	effective height;
k_0	$2\pi/\lambda$;
v_{ph}	phase velocity of propagating mode;
α'	attenuation rate (Np/m) of propagating mode.

The coordinate system is earth centered and spherical (r, θ, ϕ), so that E_r is a vertical field and H_ϕ a horizontal field perpendicular to the propagation path. There are a number of important considerations which led to (1). For the frequency band of interest for both our propagation program and noise measurement program (20–1000 Hz) the only propagating mode is the quasi-TEM mode. The TE and TM modes are highly attenuated. This is due to the fact that at these frequencies the D region during the day and the lower E region during the night can be approximated rather well as an imperfectly conducting wall. The "waveguide" width is then of the order of 60–100 km whereas the wavelength is of the order of 1 Mm resulting in the quasi-TEM mode being the only propagating mode. In addition to the direct component of the field strength there is the similar round-the-world component which travels via the longer segment of the great circle path. The expression for $(H_\phi)_R$ is

$$(H_\phi)_R \cong + \frac{IL \cos\phi}{\eta} \left(\frac{\pi\mu_0}{2c}\right)^{1/2} \left\{\frac{1}{h[\sigma_e(c/v_{ph})]^{1/2}}\right\} \cdot \left\{\frac{(1/r_e)_e}{\sin d/r}\right\}^{1/2} \exp\left[-\alpha'(2\pi r_e - d) + j\left[\omega t - k_0 \frac{c}{v_{ph}}(2\pi r_e - d) - \pi/4\right]\right]. \quad (3)$$

The total field $(H_\phi)_T$ (where $(H_\phi)_T = (H_\phi)_D + (H_\phi)_R$) gives a standing wave pattern whose amplitude variations increase as one approaches the antipode. The expression for the total field applies globally with the exception of the areas near the transmitter and near the antipode. In our measurements we have avoided these areas. Measurements by Bannister [10] show the near field being negligible beyond 1 Mm. Fig. 2 is a pictorial representation illustrating the standing wave pattern as well as the major transitions associated with sunrise and sunset. The fact that the simple model has a single propagating mode

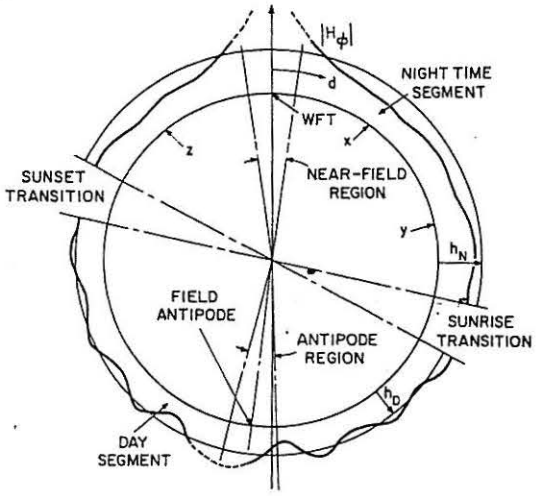


Fig. 2. Pictorial representation of the standing wave pattern for a model of the earth–ionosphere cavity.

suggests that the actual received signals should be quite stable provided that both the transmitter and receiver are on the same side of the sunlit (or darkened) hemisphere. When the receiver and transmitter are in different hemispheres the signal would to first order vary monotonically in time with a slope proportional to the difference in daytime and nighttime attenuation rates (in dB/Mm). When either the receiver or transmitter is beneath the sunrise or sunset terminator, the received signals may change relatively rapidly due to the changing mode excitation.

An experimental excitation factor E is defined as follows:

$$E = [h(\sigma_e c/v_{ph})^{1/2}]^{-1} \ (\text{mho}\cdot\text{m})^{-1/2}. \quad (4)$$

This should be not confused with the mode excitation factor A_n used in many of the earlier theoretical studies [1], [2]. The choice of the same name for two different quantities is unfortunate but since E is often used in experimental investigations we will remain with this term in this paper. E is a quantity that can be easily determined experimentally. If reasonable estimates of v_{ph} and measurements of σ_e (at the transmitter) can be made then one can deduce the effective height h. The fact that computed values of h fall in the D region of the ionosphere satisfies one's physical intuition and lends support to the analysis done in conjunction with the simple "Wait" model.

Aside from E, the other unknown in the expression for the *magnitude* of $(H_\phi)_D$ is the attenuation rate α, which is usually given in dB/Mm (where $\alpha = 8.68\alpha'$). With E and α as unknowns in the analytical expression for $(H_\phi)_D$, one can construct a simple experiment. Choosing two separated stations on the same side of the great circle path as the transmitter allows one to evaluate E and α separately. This is a technique that has been used often by the investigators of sferics. In particular, if the ratio of the magnitude of the fields measured at two sites is taken, then the excitation factor cancels out so that α

can be evaluated independently. Let the two stations be designated by x and y, then from (1), one obtains

$$\alpha = \frac{1}{d_y - d_x}\left\{10 \log \frac{\sin (d_x/r_e)}{\sin (d_y/r_e)} + 20 \log \left(\frac{|H_\phi|_{D,x}}{|H_\phi|_{D,y}}\right)\right\} \text{ dB/Mm.} \quad (5)$$

It should be pointed out that for (5) to apply the ionospheric conditions between receivers x and y must be fairly uniform (i.e., for example an all day or an all night path segment). A reasonable first approximation for $|H_\phi|_D$ if the ionosphere is variable in position and time could be obtained by simply replacing the exponential behavior in (1) by $\exp(-\int_0^d \alpha'(r,t)\,dr)$. It should be then understood that we are measuring in (5) an average value of the attenuation rate over both time and position. Typically, the single sample averages are over 4 Mm and about 1.42 h in time (this point will be expanded on later).

Equation (5) still cannot be used directly since we measure the magnitude of the field $|H_\phi|_T$ and not its direct component $|H_\phi|_D$. This point is circumvented by a suitable averaging of the measured values of $|H_\phi|_T$ over frequency. See [8] for details. The essential point of the argument is as follows. An examination of Fig. 2 shows that sufficiently far removed from the antipode region the standing wave pattern has a decaying sinusoidal behavior. To first order the position of the minimums of the pattern are proportional to the wavelength (Jones [3]). It can then be shown for receiver sites located within several megameters of the transmitter that if the frequency is uniformly selected over about a 10-Hz band, the standing wave pattern at each site will shift through more than one complete standing wavelength. It then follows that averaging the values of $|H_\phi|_T$ over frequency in a 10-Hz band will give a value very close to $|H_\phi|_D$, i.e.,

$$|H_\phi|_D \sim \frac{1}{N}\sum_{i=1}^{N} |H_\phi(f_i)|_T. \quad (6)$$

Equation (1) is used in still one other way. With two receivers equidistant from the transmitter and on opposite sides of the great circle path, one can ascertain the directional dependence of propagation. For example, we have investigated the difference in propagation in the east to west direction as compared to the west to east direction, from the expression

$$\alpha_{EW} - \alpha_{WE} = \frac{1}{d}\left\{20 \log \frac{|H_\phi|_{T,E}}{|H_\phi|_{T,W}}\right\}. \quad (7)$$

All the other quantities canceled out in the normalization provided the conditions over the total path are reasonably uniform.

It is obvious that once α has been computed, E can be calculated with (1). One final point is that both (5) and (7) must be used only under appropriate circumstances. We have been careful to use only those data taken when the direct path segment between the transmitter and receivers was entirely under daytime conditions (or under nighttime conditions). In particular the times were chosen to avoid the sunrise or sunset terminators as illustrated in Fig. 2. Thus in the absence of noise one could measure α and E accurately and knowing σ_e for a proposed transmitter location one could design an ELF communications system.

ELF MEASUREMENT PROGRAM

The ELF measurement system has evolved from an atmospheric noise measurement technique developed in 1968. Several alternatives were open for consideration in the choice of an antenna. The E field dipole antenna was rejected as a candidate for precision measurements due to the difficulty of maintaining calibration under diverse weather environments. Loop antennas with high permeability cores have on occasion exhibited effective turns–area product changes due to changes in permeability. Hence we have selected air core loop antennas with a turns–area product of 909.2 m².

A block diagram of the measurement equipment is shown in Fig. 3. During the measurement period 12-h FM tape recordings of the received signal are made. Included on the magnetic tapes are high-level reference signals for the calibration signal and the received signal in order to facilitate subsequent data analysis. A complement of band reject filters to reduce power line contamination is available so that frequency rejection may be tailored to the site. At the end of a measurement period the tapes from all sites are returned to the laboratory and analyzed on a common playback facility shown in Fig. 4 for the final estimates. The tape recording of all the data has proved valuable. It provides the freedom to alter the analysis parameters to focus on specific aspects of the data. For example, anomalous propagation effects that might be overlooked in the field in real time can be reexamined from several aspects with a playback facility.

System calibrations include a great number of details and accordingly we will mention only the essential elements. See [8] for details. The primary calibrations are accomplished in the following manner.

1) Prior to and following a recording session, precisely known signal levels, first at the transmitted signal frequency and then at the calibration frequency, are injected in series with the antenna (which is then temporarily shorted). The voltages at the input of the tape recorder are measured and from these values the relative channel gain (G_c/G_s) can be determined.

2) During the recording period ($\approx$12 h) a calibration signal $\beta(f_c)$ nominally 20 dB above the received signal is injected in series with the active antenna, and a high-level replica is also recorded on another track. This calibration signal then provides a permanent continuous monitor of system gain through the playback process. It also is a

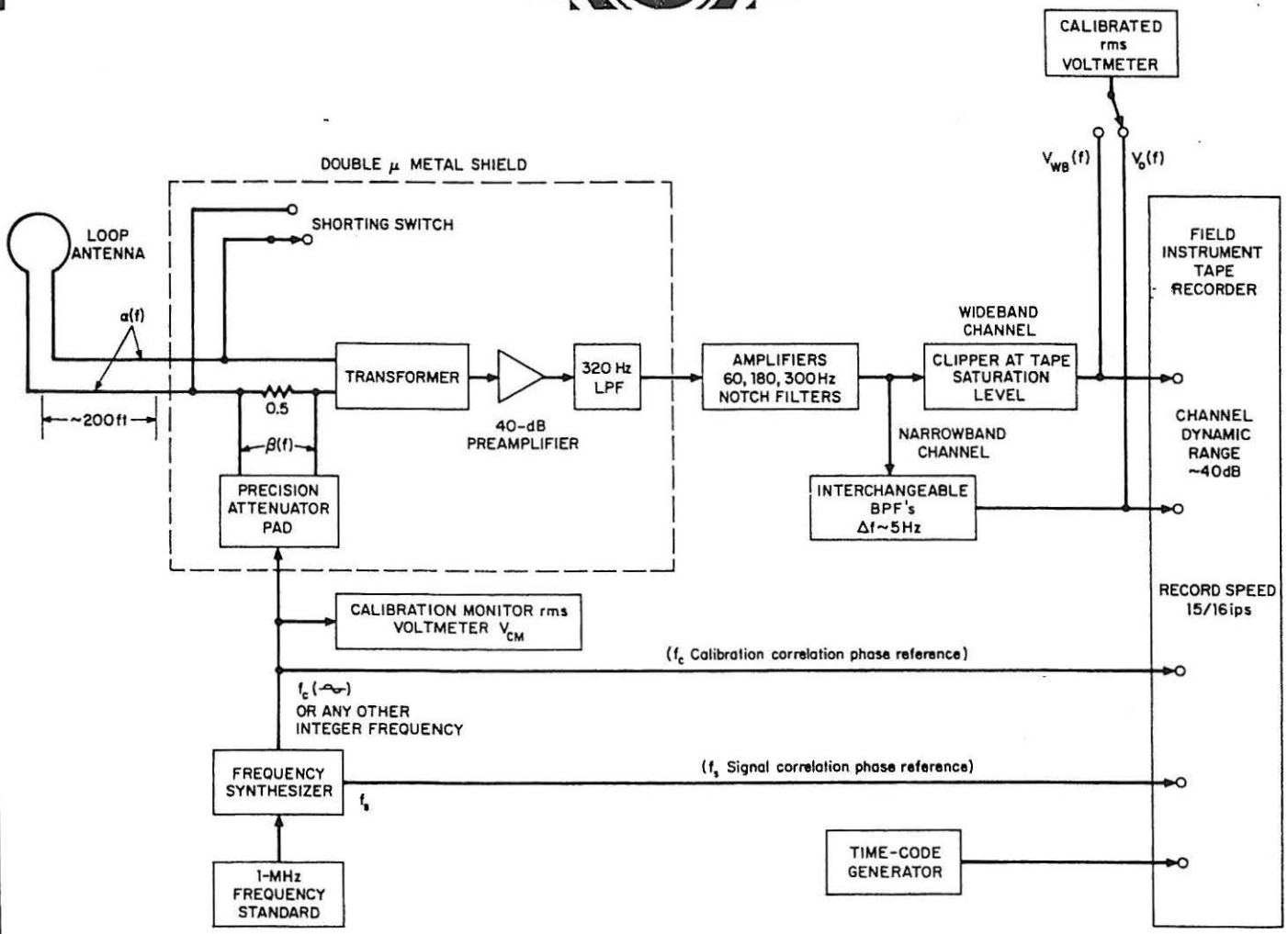


Fig. 3. Field site recording equipment.

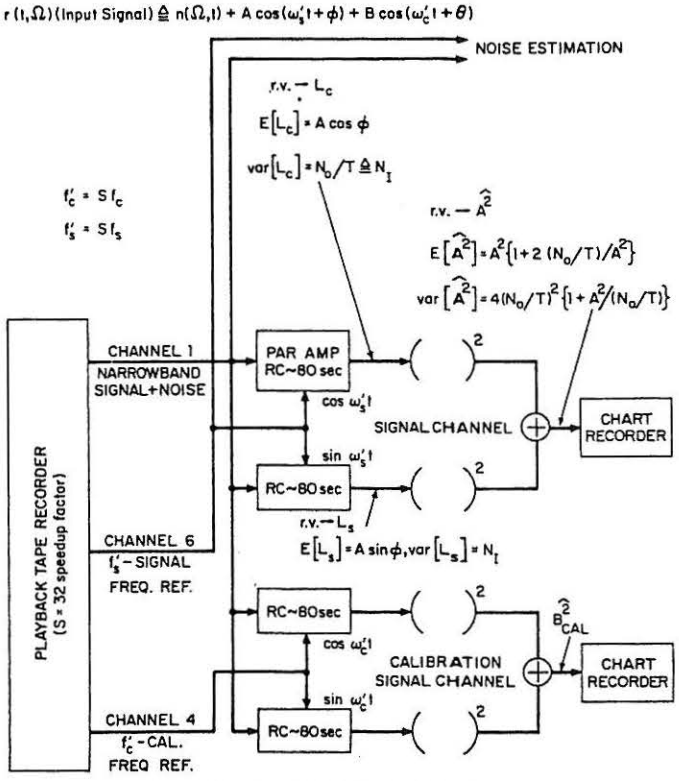


Fig. 4. Playback facility block diagram.

useful indicator for system failure and can eliminate wasted time spent on invalid data.

It can be easily shown that in the absence of noise the magnetic field intensity can then be determined from

$$|H_\phi(f_s)| = \frac{\beta(f_c)}{(2\pi\mu_0 NAf_s)}\left(\frac{G_c(f_c)}{G_s(f_s)}\right)\frac{A}{B} \tag{8}$$

where

- G_c/G_s relative channel gain at the calibration and signal frequencies;
- NA antenna turns-area product;
- $\beta(f_c)$ injected calibration signal level;
- A/B output voltage ratio from the quadrature correlator receivers in Fig. 4, A being proportional to the received signal and B to the calibration signal.

For bandwidths less than 0.01 Hz the instantaneous noise is a result of the summing the "tails" of an increasingly larger number of independent sferics. By the central limit theorem, one then expects the noise at the output of either the in-phase or out-of-phase lock-in amplifiers to approach Gaussian. The receiver output $\hat{A}^2$ is a biased estimator of the square of the signal amplitude A whose mean and

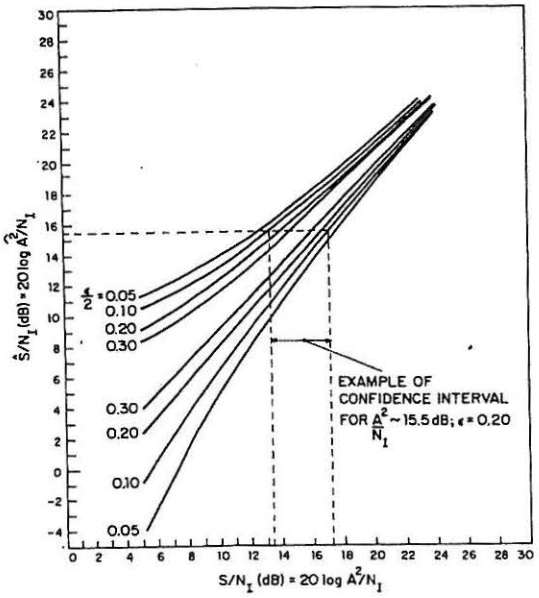


Fig. 5. Confidence curves for various confidence levels ϵ. $\hat{A}^2$ is the sample estimate of the signal power. A is the peak (rather than rms) value.

variance are given by

$$E[\hat{A}^2] = A^2 \left\{1 + 2\left(\frac{N_0}{T}\right) \Big/ A^2\right\} \tag{9}$$

$$\text{var}\,[\hat{A}^2] = 4(N_0/T)^2\{1 + A^2/N_0/T\} \tag{10}$$

where N_0 is the single-sided density for white Gaussian noise. A randomization of the phase relationship between the filtered sferics and the receiver's reference frequency leads to a lack of correlation between L_c and L_s (see Fig. 4). With L_s and L_c uncorrelated, it is easy to show (Van Trees [12]) that the cumulative distribution function for $\hat{A}^2 = L_c^2 + L_s^2$ is related to the Marcum Q function by

$$P[\hat{A}^2 < \gamma^2] = 1 - Q[A/N_I^{1/2}, \gamma/N_I^{1/2}] \tag{11}$$

where $N_I = N_0/T$. It is standard practice to derive the confidence curves from the relations

$$\frac{\epsilon}{2} = P[\hat{A}^2 \leq \gamma_L^2] = P[\hat{A}^2 \geq \gamma_H^2]. \tag{12}$$

Fig. 5 then shows the confidence curves with the parameter $A/N_I^{1/2}$ converted to dB where A is a peak (rather than rms) level. For signal to noise ratios greater than 25 dB one can use an asymptotic expression for $Q(A/N_i^{1/2}, \gamma/N_I^{1/2})$ as given by Van Trees [12]:

$$Q\left(\frac{A}{N_I^{1/2}}, \frac{\gamma}{N_I^{1/2}}\right) \simeq \frac{1}{2}\left[1 + \text{erf}\left(\frac{A-\gamma}{(2N_I)^{1/2}}\right)\right]$$

for $\gamma \gg N_I^{1/2}$ and $\gamma \gg \gamma - A$.

Thus,

$$P[\hat{A}^2 \leq \gamma^2] \sim \frac{1}{2}\left[1 - \text{erf}\left(\frac{A-\gamma}{2N_I^{1/2}}\right)\right]. \tag{13}$$

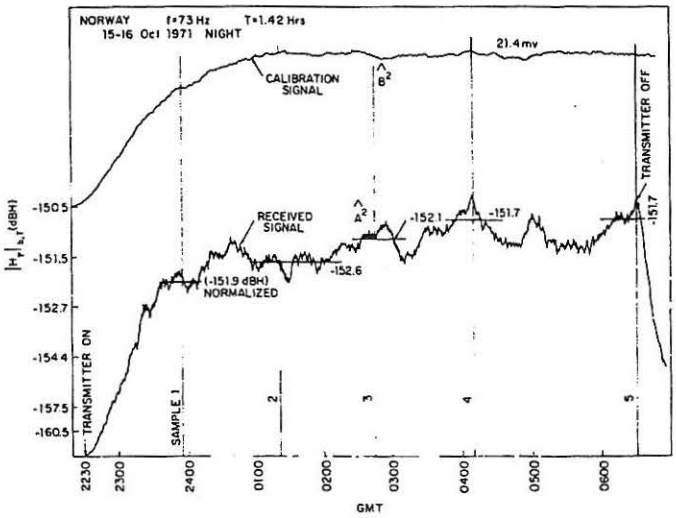


Fig. 6. Typical biased signal estimate trace. The lower curve exhibits the receiver output for the signal channel while the upper trace exhibits the behavior of the calibration signal (the scale for the upper trace has been removed).

In order to obtain accuracies on α of the order of ± 0.1 dB/Mm, one must measure the magnetic field intensities to an accuracy of the order of ± 0.2 dBH. (This results from (5) when $d_y - d_x \sim 4$ Mm.) As an example, Fig. 5 shows the 80 percent confidence interval when the measured peak signal to noise ratio is 15.5 dB. The confidence interval is from about 13.3 dB to 17.2 dB, almost a 4-dB span. The interpretation of the confidence interval is that the true signal to noise ratio falls in this interval with an 80 percent probability. It is obvious that one needs to improve the signal to noise ratio by at least 10 dB and hence one must integrate at least 10 times longer for each sample. Unfortunately, this would normally extend through a sunrise or sunset transition period, where the signal level is known to change abruptly. We have typically selected, say, a 6-h period when the whole propagation path is under uniform conditions, divided this period into 4 equispaced samples where $T = 1.42$ h, and then averaged these 4 samples. We then further average over the same period on successive days.

Fig. 6 shows the typical calibrated chart recording of the outputs from the receiver. Samples of both $\hat{A}^2$ and $\hat{B}^2$ were selected every 1.42 h (the effective integration time). After the biases have been subtracted off, a bias corrected ratio $(B^2/A^2)^{1/2}$ is then substituted into (8) and $|H_\phi(f_s)|$ computed. In order to minimize the effect of a few samples where the noise is abnormally high (due to local storms) one can use the following weighting instead of straight averaging:

$$\overline{|H_\phi^2(f_j)|} = \frac{\sum_{i=1}^{M} \frac{|H_\phi^2(f_j)|_i}{H_{N_I}^2}}{\sum_{i=1}^{M} \frac{1}{H^2_{N_I,i}}} \tag{14}$$

where $H^2_{N_I,i}$ is the ith integrated noise sample as defined

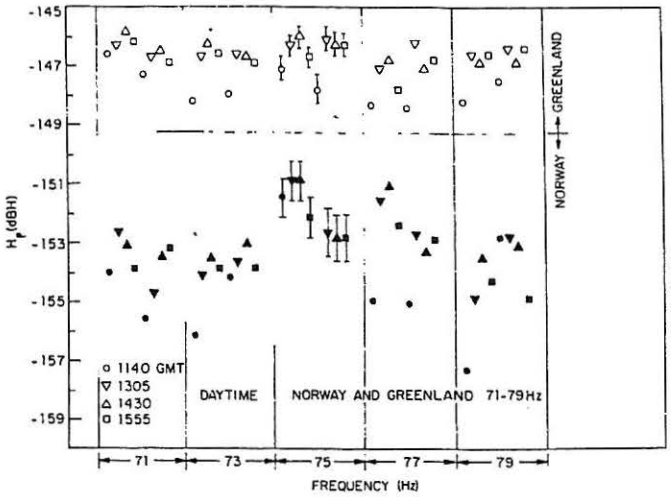


Fig. 7. Unbiased signal estimates $|H_\phi^2|_u$—Greenland and Norway daytime (71–79 Hz).

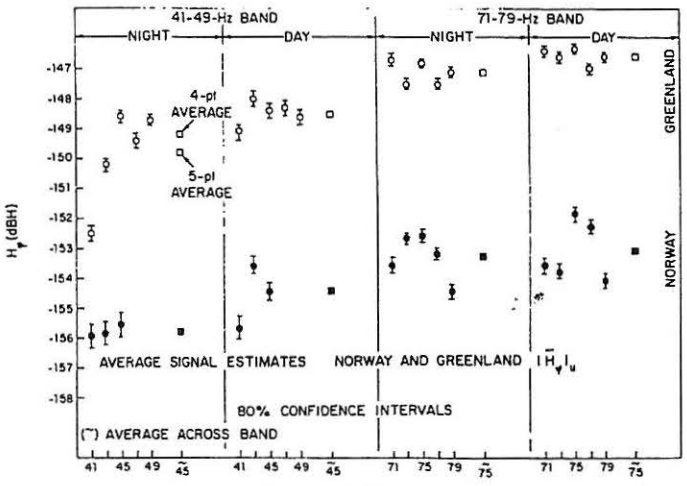


Fig. 8. Average signal estimates $|\bar{H}_\phi^2|$—Greenland and Norway. ○ corresponds to averages at each frequency and □ to the average over the 9-Hz band.

in the next section. Note that this average is over all the data at the signal frequency f_j. In order to minimize the effects of standing waves, we discussed earlier the possibility of averaging over a specified bandwidth. Specifically, we average over frequency as follows:

$$|H_\phi^2(f_m)|_D \simeq \overline{|H_\phi^2(f_m)|} = f_m^2 \frac{1}{2J+1} \sum_{j=1}^{2J+1} \frac{|H_\phi^2(f_j)|}{f_j^2} \quad (15)$$

where f_m is the center frequency. If desired (see [8]) one can derive composite confidence curves for $\overline{|H_\phi^2(f_j)|}$ and $\overline{|H_\phi^2|}$.

In the computation of average α and E from (5) and (1), one must then use the averages for each site as computed in (15). In order for the resulting average α and E along with their error bars to have any physical significance, one must be reasonably sure that the actual signal level during these extended time periods was in fact quite stable (and approximately equal from day to day). This is, of course, a key issue and we must in fact look at the scatter of all the individual sample values and try to determine roughly how much of the variation is attributable to noise and how much can be ascribed to actual signal level changes. This can be accomplished in the following way as illustrated in Fig. 7. Let us first ignore the points at 1140 GMT since these points correspond to a period in which the transmitter is still in darkness whereas most of the propagation path is under daytime conditions. With each sample signal and integrated noise estimate known, one can determine the individual sample confidence intervals (representative 80 percent confidence intervals are plotted for 75 Hz). If the confidence intervals have a common overlapping band then it would be a reasonable assumption that the true signal level falls in this band. If, on the other hand, the confidence intervals have a high degree of disjointness (no evident common overlapping interval) it would be safe to assume a significant variation in the true signal level. For the Greenland data one can easily see that the true average value is most likely about −146.6 dBH and has high stability even though the data was taken over ten days. The Norway data shows more variation (in keeping with a poorer signal to noise ratio). However, there does appear to be about 5 abnormally high signal estimates. This behavior is not uncommon for auroral region sites where abnormal signals occur and tend to be on the high side. Fig. 8 shows the average values $\overline{|H_\phi^2(f_j)|}$ as well as $\overline{|H_\phi^2(f_m)|}$ for Norway and Greenland and from these values α and E were computed. The 80 percent confidence limits are also shown.

The last series of measurements (Phase IV) attempted to assess the effects of the sunrise or sunset terminator intersecting the propagation path in addition to obtaining some crude statistics of the signals at remote sites (Greece, Norway, and Saipan). A simplified, but to first order accurate, description of the differences in daytime versus nighttime ELF propagation is the following. The height of the lossy upper "waveguide" boundary depends on the presence or absence of sunlight. Under nighttime conditions, the D region ionosphere (50–90 km) is very residual and the uppermost part of this region along with the lower portion of the nighttime E layer (90–120) form the effective upper boundary. Shortly after sunrise the D layer becomes almost fully developed with the effective boundary being lowered down to somewhere between 50–75 km. Equation (1) implies that the field intensity through the excitation factor E is inversely proporational to the effective waveguide height. However, one also expects α to increase with a decreasing guide height h due to the rapidly increasing charged particle–neutral collision frequencies at the lower heights. Thus one expects during the daytime to have a better excitation factor but a larger attenuation rate and for nighttime just the reverse. For mixed cases one can get some enhancement or degradation of the signal depending on the relative locations of the transmitter, receivers, and sunrise–sunset terminator in respect to the propagation path. For example, a high signal strength would result if the transmitter area is in daylight (enhanced excitation) whereas the major portion

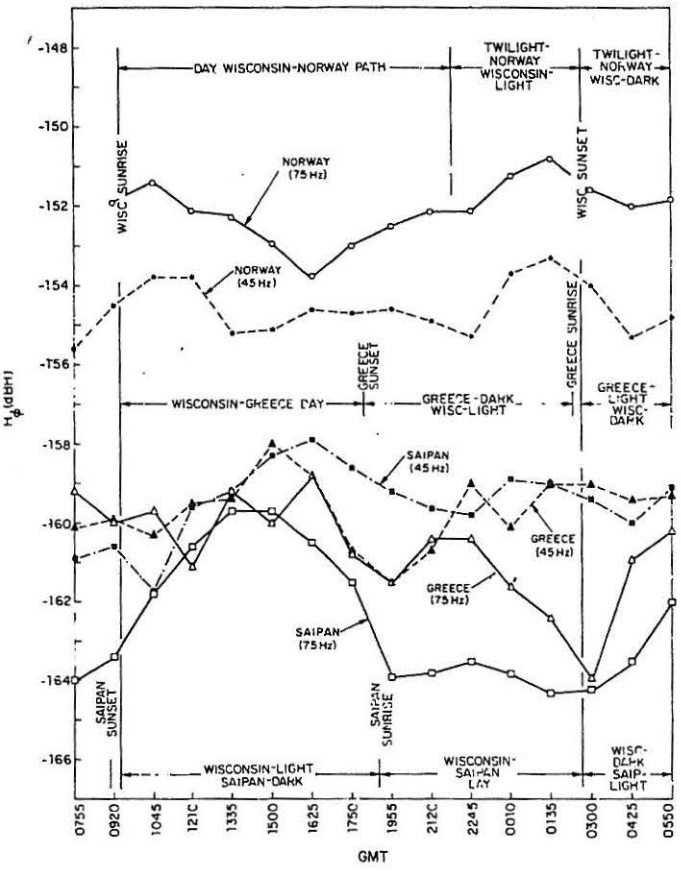


Fig. 9. Signal averages for each selected sample time. (75 Hz) refers to the averages over the 71–79 Hz band and (45 Hz) to the averages over the 41–49 Hz band.

of the propagation path is mainly in darkness (low attenuation rate). Conversely, low signal would result if the transmitter were in darkness and the path were in daylight. Fig. 9 summarizes some of the data collected during the most recent tests. Averages were taken over signal estimates collected at the same time on successive days and plotted as shown. (The signal strengths in Greece are of the same magnitude as Saipan only because the antenna pattern was chosen to point towards Saipan leaving Greece on the steep slope of the pattern.) With a little thought the signal level variations shown in these figures can be seen to be compatible with the previous simple description of the propagation during uniform or mixed conditions. An interesting case of signal degradation occurs at Greece at 75 Hz near 0300 GMT. It should, however, be noted that this occurred when the sun was rising in Greece and simultaneously setting in Wisconsin. A portion of the approximately 2-dB drop is attributable to phase shifts during a single integration period at both ends of the path since it is known that a correlation receiver will then provide an estimate lower than the actual level (remember that $T = 1.42$ h).

NOISE ANALYSIS

Accurate knowledge of the noise intensity (at the signal frequency) is necessary for the following two reasons.

TABLE II
COMPARISON OF PROPAGATION PARAMETERS

	RCA (1966–1967) North Carolina–Iceland Path	MIT (1971 Spring) Utah–Hawaii Path	MIT (1971 Fall) Greenland–Norway Path
45 Hz			
α_D		1.2 dB/Mm	1.0 dB/Mm
E_D		11.75×10^{-4}	11.48×10^{-4}
α_N		0.8	1.0
E_N		7.69×10^{-4}	10.7×10^{-4}
75 Hz (MIT)[a]			
α_D	1.27 dB/Mm	1.5	1.4
E_D	6.25×10^{-4}	10.33×10^{-4}	10.4×10^{-4}
78 Hz (RCA)			
α_N	1.01	0.9	1.3
E_N	4.93×10^{-4}	6.79×10^{-4}	8.6×10^{-4}

[a] One reason for the differences in the E values for RCA and MIT is due to the conductivity σ_e being different for the different transmitter areas.

1) The estimate of signal at the output of the receiver is a biased estimator (i.e., $E(\hat{A}^2) = A^2 + 2(N_0/T)$). Accordingly, the bias that is determined from the noise intensity N_0 and the effective integration time T must be subtracted from the sample value $\hat{A}^2$ to give the unbiased estimate of A^2. Typically these biases run from 0.1 to 0.6 dB.

2) The confidence limits on each estimate $\hat{A}^2$ depend on the ratio A^2/N_I, where $N_I = N_0/T$. Accordingly, a small confidence interval for A^2 requires an even smaller confidence interval for N_I.

The noise at ELF is generated by lightning strokes from storm centers all over the globe. The wideband noise is extremely impulsive and decidedly non-Gaussian [14] and, consequently, care must then be taken in the method of measuring this noise. The description of the noise intensity measurement procedure is fully described in [8]. It suffices to state that the sample noise intensity $H_{N_0}^2$ (referred to an equivalent input H_ϕ field in units of dBH/(Hz)$^{1/2}$) is computed each effective integration period T and at a confidence level $\epsilon/2 = 10$ percent the confidence interval will be ± 0.1 dB. The integrated noise is given by

$$H_{N_I}^2 = H_{N_0}^2/T.$$

SUMMARY OF PRINCIPAL RESULTS

The measured average propagation parameters are summarized in Table II. As previously discussed, these parameters are required for the application of the Wait model as embodied in (1). The values of α and E to be used for prediction purposes depend on the proposed site location and propagation path. With the values we have computed on earlier tests it has been our experience that the predictions for the following tests were generally within about 1 dB. The worst case prediction was for Saipan where the predicted 75-Hz daytime value was -161.8 dBH and the measured value was about -164.0 dBH (a 2.2 dB difference). (Note that as an example if

Extremely Low Frequency (ELF) Propagation Measurements Along a 4900-km Path

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Abstract—Extremely low frequency (ELF) electromagnetic wave propagation was investigated by measuring the amplitude of a CW signal transmitted from the Sanguine site in North Carolina to receiving sites located in New York State, Labrador, and Iceland. The attenuation factor α and the reciprocal of the excitation factor $h_i(\sigma_e S_0)^{1/2}$ were determined. Data for daytime, nighttime, and sunrise transition paths were obtained. The attenuation factors obtained for 78 and 156 Hz are compared with the value of α obtained from measurements of atmospherics. The attenuation values at 78 Hz of 1.29 and 1.01 dB/1000 km, and a value of 0.75 dB/1000 km at 45 Hz, obtained by interpolation of results of this and other experiments, were used in Sanguine systems analysis.

I. INTRODUCTION

DURING the periods from November 29, 1966 to December 21, 1966 and January 4, 1967 to February 4, 1967, the Sanguine [1] pole line antenna in North Carolina was excited and the horizontal component of the magnetic field H_ϕ was measured at three sites. These sites were located in Point au Feu, N. Y.; Goose Bay, Labrador; and Keflavik, Iceland. By a least squares fit of the data to the ELF propagation equation, the daytime and nighttime attenuation α and the reciprocal of the excitation factor $h_i(\sigma_e S_0)^{1/2}$ were determined. This propagation experiment was conducted to obtain estimates of attenuation rates for Sanguine system analysis.

Some propagation data had been obtained from previous RCA tests. However, these tests were not designed specifically for propagation measurements. Tests in winter and early spring of 1962 demonstrated that four-character-coded ELF signals could be received with a trailing antenna in the operational environment of a submarine. Close-in propagation data (less than 1000 km) were obtained in 1963, 1964, and 1965 when the pole line antenna was activated at various times in support of earth conductivity measurements and submarine receiving sensor development. These measurements showed that ELF signals were very stable over a 849-km path to Riverhead, N.Y., and indicated a possible skew in the antenna pattern. This skew in the antenna radiation pattern was found to be 10° counterclockwise when antenna pattern measurements were conducted during March and April 1966. The Naval Underwater Systems Center also found a pattern skew in the 22-km line at the Wisconsin Test Facility.

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II. PROPAGATION EXPERIMENT

A. Propagation Equation

By measuring field strengths at several sites, preferably along the same great circle, α and 20 log $h_i(\sigma_e S_0)^{1/2}$ can be determined from a least squares fit to the propagation equation expressed in logarithmic form. A first-order approximation to the propagation equation for a horizontal ELF antenna in a bounded earth-ionosphere waveguide can be derived from Wait [2]:

$$H_\phi = \frac{Ilf}{2\eta}\left(\frac{2\pi\mu_0}{c}\right)^{1/2} \times 10^{-3}\,\frac{\exp\,-\,(0.1151\,\alpha r)}{r^{1/2}} \cdot\left(\frac{r/r_e}{\sin r/r_e}\right)^{1/2}\frac{1}{h_i(\sigma_e S_0)^{1/2}}\cos\phi \quad (1)$$

where

- H_ϕ horizontal component magnetic field strength, A/m;
- I pole line antenna current, A;
- l length of pole line, 176 km;
- f frequency, Hz;
- η free space impedance, 120 π Ω;
- μ_0 free space permeability, 4 $\pi \times 10^{-7}$ H/m;
- c 3×10^5 km/s;
- α attenuation rate, dB/km;
- r distance from transmitter, km;
- r_e radius of earth, 6371 km;
- h_i effective height of the ionosphere;
- S_0 mode factor = V_{ph}/C where V_{ph} is the phase velocity;
- σ_e effective earth conductivity under the pole line;
- $\cos\phi$ antenna pattern factor, ϕ is the angle between the direction of propagation path and the electrical axis of the horizontal antenna.

Rearranging terms and expressing the equation logarith-

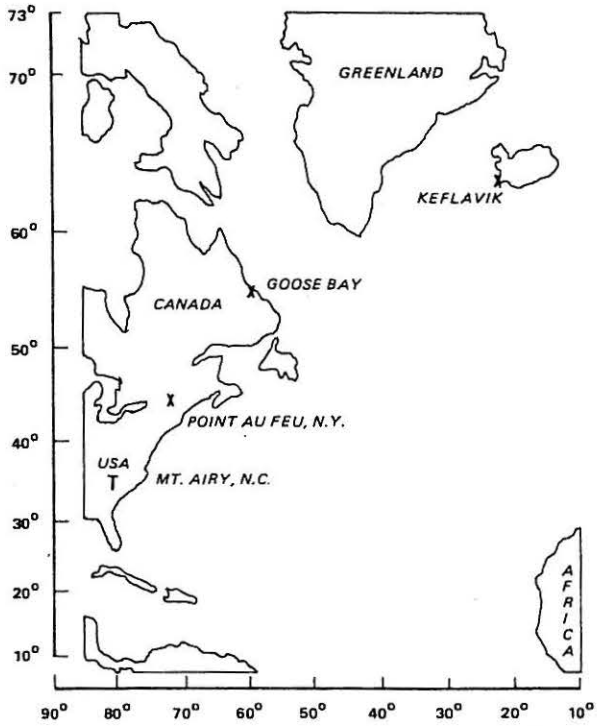


Fig. 1. Location of transmitting and receiving sites.

mically, we obtain

$$20 \log \left[H_\phi r^{1/2} \left(\frac{\sin r/r_e}{r/r_e} \right)^{1/2} \frac{1}{\cos \phi} \right]$$

$$= \left\{ 20 \log \left[\frac{Ilf}{2\eta} \left(\frac{2\pi\mu_0}{c} \right)^{1/2} \times 10^{-3} \right] \right.$$

$$\left. - 20 \log \left[h_i (\sigma_e S_0)^{1/2} \right] \right\} - \alpha r. \qquad (2)$$

Equation (2) is linear with slope α and intercept

$$20 \log \left(\frac{Il}{2\eta} \left(\frac{2\pi\mu_0}{c} \right)^{1/2} \times 10^{-3} \right) - 20 \log h_i (\sigma_e S_0)^{1/2}.$$

α and the term $[h_i(\sigma_e S_0)^{1/2}]^{-1}$ denoted as the excitation factor are propagation parameters of interest for Sanguine systems analyses.

B. Design of Experiment

Fig. 1 shows the location of the transmitter and the three receiving sites. ELF signals were transmitted at two frequencies, 78 and 156 Hz. The transmission schedule was designed to obtain the maximum amount of all-daylight path propagation data possible for that time of year. Transmissions usually took place over a period of about 16 h with 1 h on and $\frac{1}{2}$ h off. Ten h of data were obtained each day. The frequency was changed each transmission hour. However, during the last three weeks, the transmission schedule was rearranged to obtain more data at 78 Hz.

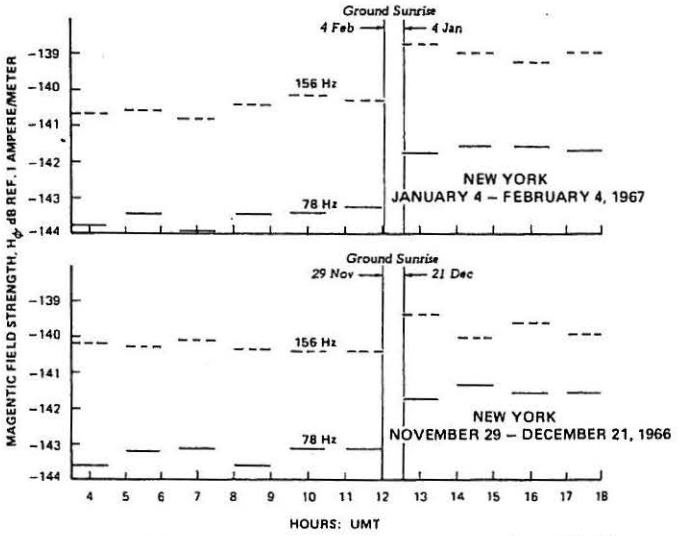


Fig. 2. Magnetic field strength at Point au Feu, N. Y.

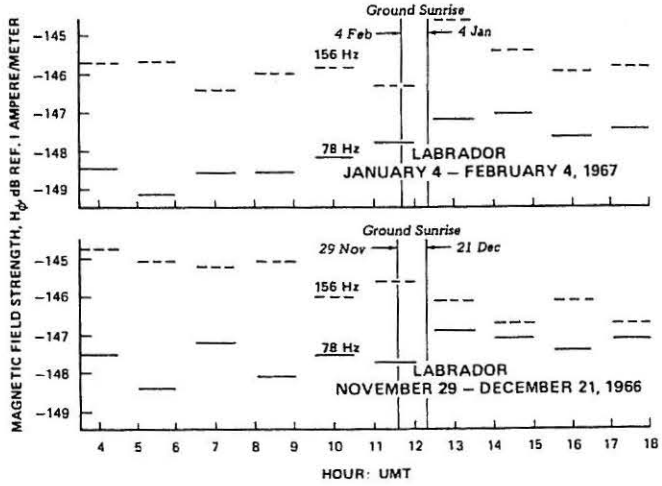


Fig. 3. Magnetic field strength at Goose Bay, Labrador.

III. RESULTS OF FIELD STRENGTH MEASUREMENTS

A. Field Intensity at Each Site

Figs. 2, 3, and 4 give the average values of field intensity at each site for each hour. The effect of the change from night to day ionospheric heights is shown in Fig. 2 by the increase in signal level at both frequencies after sunrise. The increase in signal is greater at the lower frequency, which is to be expected, since after sunrise there should be a greater increase in attenuation at the higher frequency. The propagation path is longer, and the effect of increased attenuation after sunrise begins to show up especially at 156 Hz at Iceland. After 1230, the path from the transmitter to Iceland was an all-daylight path, and the attenuation should increase after sunrise in New York. (Sunrise at the transmitter is about 5 min later than at New York.) The signal at 156 Hz does decrease, but only after a time lag; the signal does not decrease until the

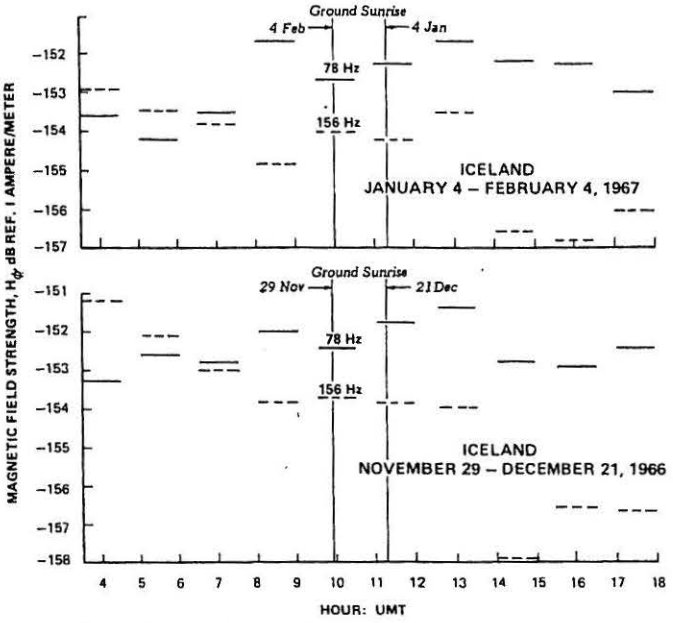


Fig. 4. Magnetic field strength at Keflavik, Iceland.

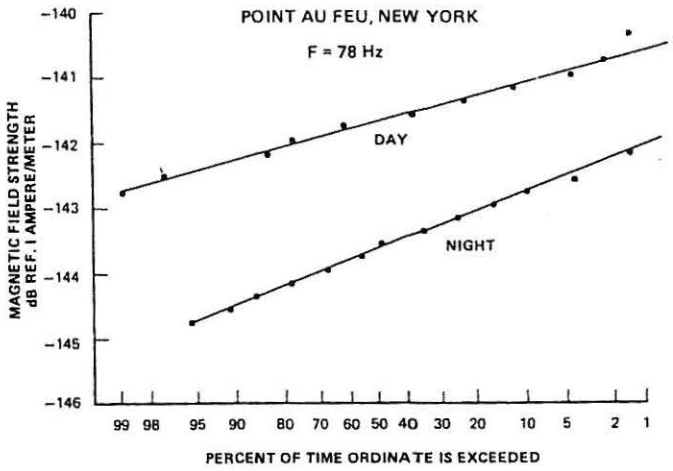


Fig. 5. Cumulative probability distribution of field strength data for 78 Hz, Point au Feu, N. Y.

second transmission hour after New York sunrise. Considering the first three transmission hours as nighttime propagation and the last three as all daylight, the 78-Hz signal increased for the all-daylight path during the January 4–February 4, 1967 period, while for the November 29–December 21, 1966 period the signal remained the same.

The cumulative probability distributions of the 78-Hz field intensity data for the daylight path hours and night path hours for Point au Feu and Keflavik are plotted in Figs. 5 and 6.

B. Determination of α and $h_i(\sigma_e S)^{1/2}$

From a least squares fit to the data, α and $h_i(\sigma_e S_0)^{1/2}$ were determined for each transmission hour. The values of α are plotted in Fig. 7(a) and (b). The value of the ex-

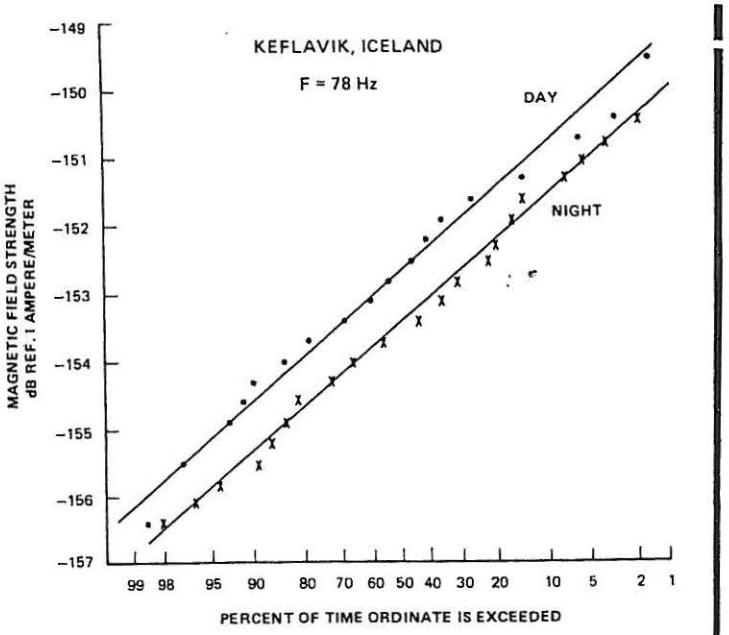
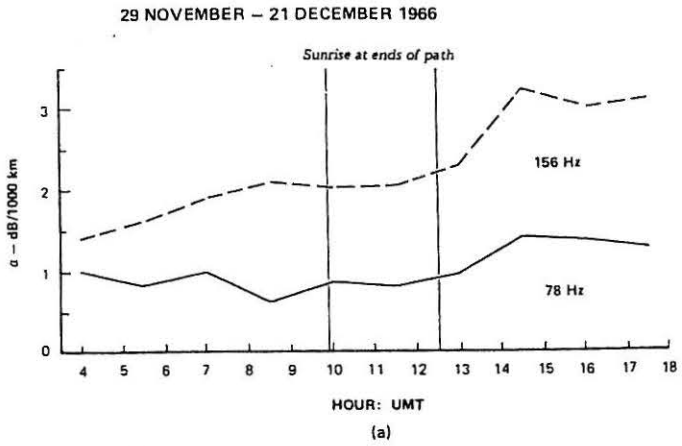


Fig. 6. Cumulative probability distribution of field strength data for 78 Hz, Keflavik, Iceland.



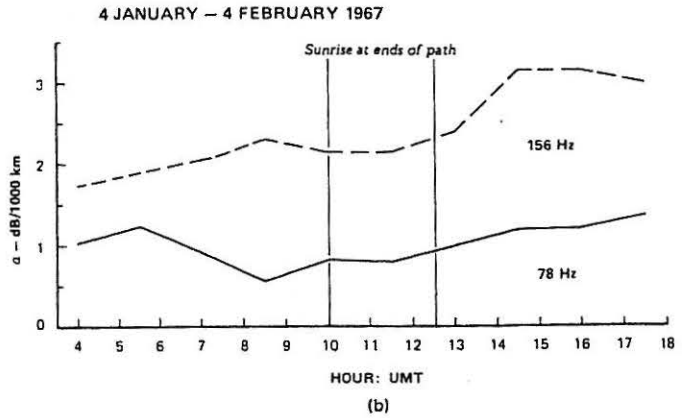


Fig. 7. Attenuation factor α as a function of transmission time.

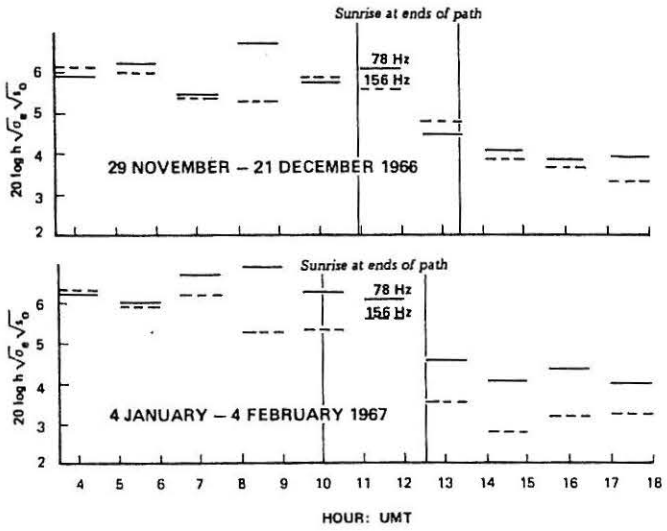


Fig. 8. Excitation factor [dB ref km (mho/m)$^{1/2}$] as a function of transmission time.

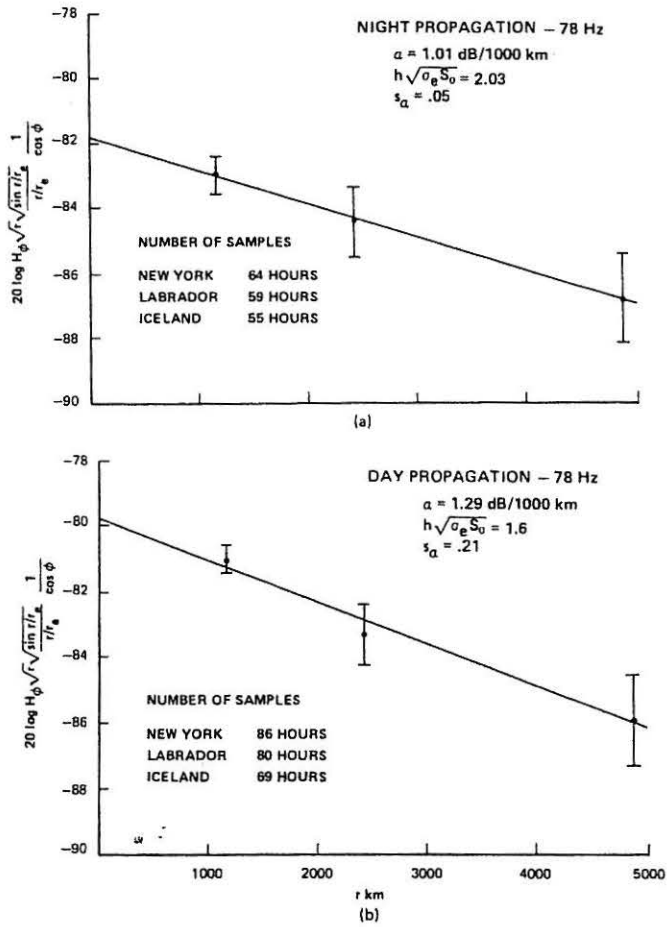


Fig. 9. Least squares fit to 78-Hz propagation data.

citation factor 20 log $h_i(\sigma_e S_0)^{1/2}$ is plotted in Fig. 8. The method for least squares employed for the determination of α and $h_i(\sigma_e S_0)^{1/2}$ is described in Acton [3].

The plots of field intensity and excitation factor versus transmission hour indicate that the first 3 h can be considered an all-night path and the last 3 h an all-day path, while the middle 4 h contain a day–night transmission path. Combining the data for the November–December and January–February periods gives the values shown in the least square plots [Figs. 9(a),(b) and 10(a),(b)] where s_α is the standard deviation of α. The standard deviations of the field strength data for each location are also given in Figs. 9 and 10.

IV. CONCLUSIONS AND DISCUSSION OF RESULTS

A. Attenuation Factors

The attenuation factors, estimated from the least squares fit for North Carolina–New York–Goose Bay–Keflavik propagatoin data, are compared with the attenuation curves given in Chapman *et al.* [4, fig. 3(a)]; see Fig. 11. In addition, α data, obtained at 620, 750, and 940 Hz by RCA using the Navy VLF antenna at Jim Creek, and α values at 400 Hz obtained by Space General Corporation [5] using a horizontal antenna, are also plotted in Fig. 11. Thus, α estimates from atmospherics can be compared with α estimates from transmitted signals. The nighttime values of α obtained from transmitted signals are in substantial agreement with the values deducted from atmospheric measurements by Chapman and Marcario, while the daytime values are closer to the two station atmospheric values of Challinor and Jean. White and Willim [6], using the Sanguine Wisconsin Test Facility, obtained attenuation factors over two paths, at frequencies of 45 and 75 Hz, and compared their 75-Hz values with the values of α at 78 Hz for the North Carolina–Iceland path. The nighttime values agree with values obtained from both the Utah–Hawaii path and the Greenland–Norway paths, while the daytime attenuation is 0.2 dB lower than the Utah–Hawaii value and 0.2 dB higher than the Greenland–Norway value. Until the recent Lincoln Laboratory measurements, the RCA value for 78 Hz, and a value of 45 Hz obtained by interpolation of the data presented in Fig. 11 were used for Sanguine analysis. With the data now being obtained by Lincoln Laboratory and the Naval Underwater Systems Center using the Wisconsin Test Facility, the data presented in this paper, and the past data from atmospherics, the range of estimation of ELF attenuation rate for Sanguine System Analysis has been narrowed, particularly at the frequencies of interest, 45 and 75 Hz.

B. Day and Night Excitation Factors

The ratio of the day excitation factor to the night excitation factor was 1.3 at both frequencies.

C. Stability of ELF Signals

The field intensity measurements show that for the short path to Point au Feu, N.Y., ELF signals were very stable. The standard deviation of the mean field strength

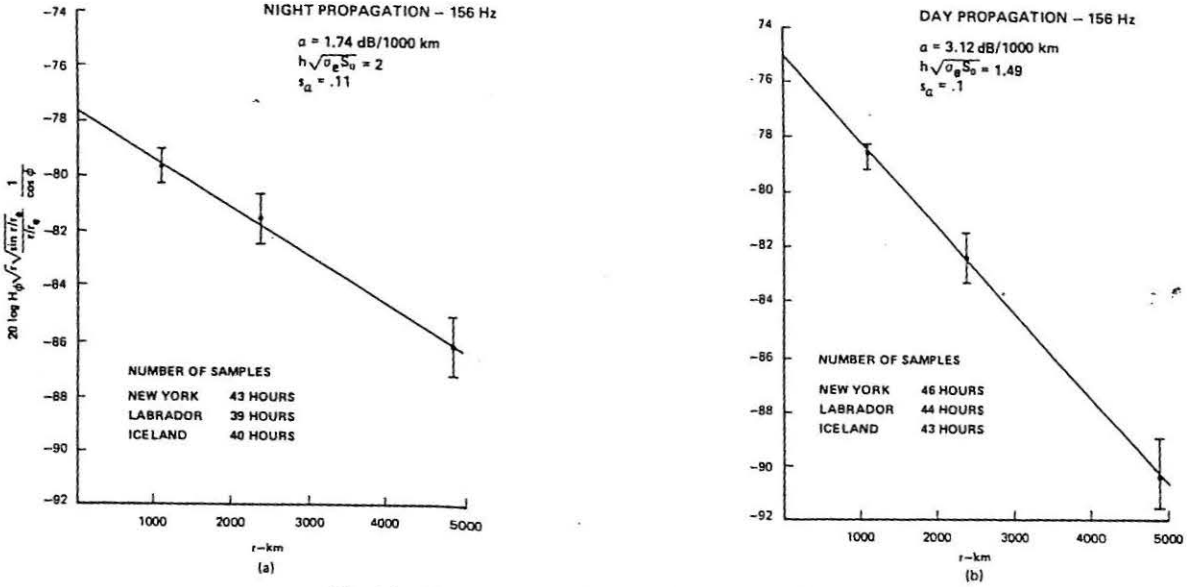


Fig. 10. Least squares fit to 156-Hz propagation data.

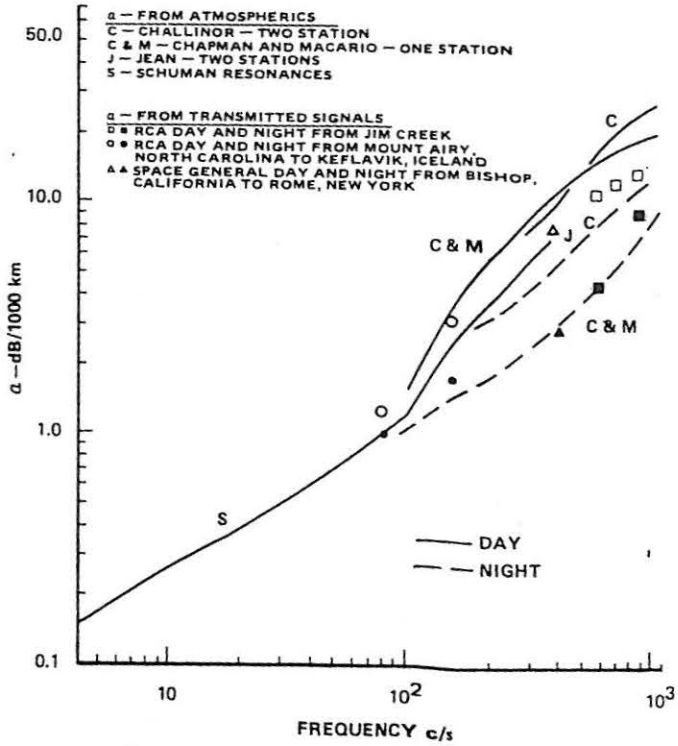


Fig. 11. ELF attenuation measurements.

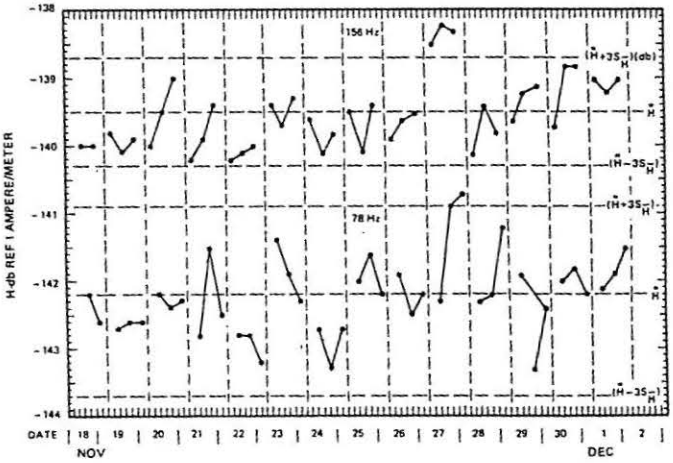


Fig. 12. ELF reception at Riverhead, N. Y., 1964.

was 0.6 dB or smaller. Signal-to-noise ratios at the New York site were in order of 20–30 dB. It is surmised that if signal-to-noise ratios of 30 dB or greater could have been attained in Iceland, determination of the effects of ionospheric fluctuations on the attenuation and excitation factors would have been possible.

For example, during the course of some previous Sanguine tests in which ELF transmissions from the North Carolina pole line were monitored at Riverhead, N.Y. for a period of 13 days (November 18–December 2, 1964) from the hours 2000 to 01000, an apparent propagation anomaly was detected. There was an increase in signal strength on day nine (November 27), Fig. 12. The values for the 3 h where 156 Hz was transmitted were all greater than three standard deviations above the mean for the 13 days, while at 78 Hz for 2 out of 3 h the signal levels were three standard deviations above the mean. The reception of HF communications signals by RCA Communications at Riverhead for that night was checked, and there were indications that some sort of ionospheric disturbance might have taken place. Checks with other sources did not give any positive correlation of the anomaly with geophysical disturbances. It was found from ELF atmospheric noise measurements that were being carried out at Riverhead that atmospheric noise at 35, 94, and 154 Hz increased during these day nine hours. However, estimates of signal-to-noise ratio indicated that the apparent change in field strength was

too great to be attributed to the increase in atmospheric noise. A supposition is that something occurred in the ionosphere to improve ELF propagation. It could be a decrease in attenuation factor or an increase in excitation factor or both. The increase in excitation seems more likely to be the major effect, since a decrease in nighttime attenuation factor of 1.4 dB/1000 km at 156 Hz would be required to account for the increased signal strength.

ACKNOWLEDGMENT

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Lawrence H. Ginsberg (A'51–SM'56) was born in New York, N. Y., in 1922. He received the B.S. degree in physics from the City College of New York, New York, N. Y., in 1947, and the M.S. degree in physics from New York University, New York, N. Y., in 1950.

During 1947–1948 his work as a Physicist at the U. S. Naval Proving Grounds, Dahlgren, Va., was concerned with static testing of rocket motors and X-ray radiography. As a Research Assistant at New York University he did millimeter-wave research. From 1951 to 1953 he was a Microwave Engineer at Fairchild Guided Missiles Division. From 1953 to 1958 he was at Stavid Engineering, Plainfield, N. Y., where he engaged in microwave antenna research and development; directed studies of IFF, radar ECM, and anti-jamming; and headed a small research and analysis group. In 1959 he joined RCA Laboratories, Princeton, N. J., as a member of the Technical Staff to work on Project Pangloss, which later evolved into Project Sanguine. At RCA he was engaged in submarine EM noise, atmospheric noise, ELF propagation, and earth conductivity studies and analysis of ELF communications systems. He was in charge of the communication and propagation data analysis for the first experiment with the North Carolina Sanguine antenna, which demonstrated that ELF signals could be received by a deeply submerged submarine. Since October 1970 he has been a member of the Professional Staff of the Center for Naval Analyses, Arlington, Va., where he has performed analysis of Naval Tactical C^3 systems requirements, jamming of tactical data links, undersea and satellite communications, and strategic C^3 requirements.

the α were increased to 1.7 dB/Mm from 1.5 dB/Mm the agreement would be excellent.)

A principal conclusion of our study, then, is that we can predict the average signal strengths at various sites with acceptable accuracy. A few comments are necessary to place some of the differences observed in the table in their proper perspective. The differences in attenuation rates are mainly a reflection of the quite different paths over which the measurements were made. For example, the Greenland–Norway segment is an auroral path with the north–south antenna being the primary radiator whereas the Utah–Hawaii path is a temperate zone path with the east–west antenna being the main source. Since the Utah–Hawaii path has a well developed daytime D region ionosphere a relatively high attenuation rate can be expected. The auroral region Greenland–Norway path has a poorly developed D region since the sun's zenith angle was always greater than 80°. This results in a lower value of the daytime attenuation rate. At night in the auroral region both the attenuation rate and the excitation factor are significantly higher than those measured in the temperate latitudes. We suggest that the cause of these higher parameters at the higher latitudes is an enhanced nighttime D region due to electrons precipitating from the magnetospheric radiation belts. At present we are trying to correlate the observed nighttime signal variability with magnetic storm activity.

The accuracy of the attenuation rates is about ± 0.1 dB/Mm provided the hypothesis on the stability of signals is accurate. The excitation factor E includes the term h, which is the effective height of the uniform earth–ionosphere waveguide. Realistically, the ionosphere above the path is more variable with position, so it seems reasonable that lowering or raising the "height" of the ionosphere above either the transmitter or above the receiver region will change the received signal intensity. Perhaps a first approximation would be to replace h by $(h_T h_R)^{1/2}$ where h_T and h_R are the effective heights above the transmitter and receiver. Then differences in the computed values of E could partly be interpreted as arising from h_R being different at the auroral and temperate zone receiver locations. (Note also that near field measurements indicate that the conductivity under the transmitter is anisotropic $\sigma_{NS} \neq \sigma_{EW}$.) It should be realized however that an error in the estimation of E is usually not as disastrous as an error in α, for the simple reason that the error in α is multiplied by the distance, which might be from 6 to 16 Mm.

As far as the propagation channel characteristics are concerned, the 70-Hz band is clearly preferable to the 40-Hz band for ranges less than 8 Mm. Not only are the received signal levels higher at 75 Hz, but the atmospheric noise is lower. It is also observed that the nighttime signal variability for 75 Hz is significantly less than at 45 Hz. (Up to this point we have not discussed the fact that in general the daytime values are quite stable whereas the nighttime values occasionally show significant variation. The point is discussed more fully in [6] and [8].)

There was some question concerning the directional behavior of the attenuation rate as a consequence of the earth's magnetic field. Careful bidirectional measurements in Utah and Nova Scotia revealed that the differences in the east to west versus the west to east attenuation rate is less than can be measured by our equipment. At present we assert that at both 45 and 75 Hz, $|\alpha_{EW} - \alpha_{WE}| \lesssim 0.2$ dB/Mm.

In addition to amplitude we have been measuring the phase history from the quadrature outputs of the receiver. The accuracy of most phase estimates is of the order of $\pm 5°$. Therefore, we can discern the magnitude of the phase shifts associated with the sunrise–sunset terminators crossing the transmitter or receiver locations. Our results indicate that the phase changes slowly while the path is under uniform conditions and most rapidly when the terminator intercepts the path. The phase changes as measured at the receiver would be given by

$$\Delta\phi(d) = k_0 \Delta \left(\int_0^d c/v_{ph} \delta d \right)$$

where

$$k_0 = 2\pi/\lambda.$$

Theoretical studies [2] have indicated that $(c/v_{ph})_{\text{Day}} - (c/v_{ph})_{\text{N}} = 0.1$ for both 45 and 75 Hz. Using this difference alone in (16) the subsequent phase shift computations can be shown to fit the observed data very well. As a point of reference, the observed diurnal phase change is approximately $\Delta\phi \simeq 50°$ (as measured in Norway), 80° (Greece), and 100° (Saipan) at 75 Hz. [6] gives more detail on the phase shift histories.

Another concern to the communicator would be signal distortion over the signaling bandwidth. In a recent paper Galejs [13] describes the possibility of pronounced "absorption" bands due to F region reflections for nighttime propagation. These reflections would show up as absorption peaks on the α versus frequency curve and with rapid changes (at the resonance peaks) on the (c/v_{ph}) versus f curve. Data from our tests indicate that *strong* absorption bands are not in evidence (as an example, compare the Greenland data in Fig. 7). We suggest that the actual nighttime E and F region profiles, which are more smoothly varying with altitude (as compared to Galejs' models), give a much reduced resonance effect. In addition the F region varies in the horizontal direction as well, so that the local resonance 'peak' would also vary with horizontal displacement. The net effect over a long path would be a relatively smooth effective value α or c/v_{ph} versus f curve. In this case distortion would not affect a wide-band ELF signal to any degree.

Another category of potentially deleterious effects are those associated with the various types of abnormal ionospheres resulting from various classes of solar emissions. In particular, we are interested in those events which might prohibit communications for a matter of at least a few hours. This class of uncertainty can only be resolved by setting up a receiver and receiving signals

continuously over a period of months at least. We have been unfortunate in that the periods we selected to perform our experiments have all been relatively "quiet" in terms of abnormal ionospheric behavior. However, the data we do have shows no clearly identifiable periods of serious signal degradation. We do, however, strongly advocate a program which routinely collects signal and noise data over a long time. It is our feeling, however, that a considerably larger transmitter than the present WTF will be necessary to resolve the ambiguities introduced as a consequence of the noise, particularly at ranges beyond 6 Mm.

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Mr. Willim is a member of Eta Kappa Nu.

Far-Field Extremely Low Frequency (ELF) Propagation Measurements, 1970–1972

PETER R. BANNISTER, MEMBER, IEEE

Abstract—For the past 3 years, we have participated in various extremely low frequency (ELF) propagation tests. During these tests, receiving sites were located in Connecticut, North Carolina, Maine, Utah, Nova Scotia, California, Greenland, the Virgin Islands, Alaska, Norway, Hawaii, Greece, and Saipan. Measurements have also been taken sporadically in Connecticut since June 1970. At each location, the horizontal magnetic field strengths were measured at a band of frequencies centered at 45 Hz and 75 Hz in order to determine the average attenuation rates and relative excitation factors for daytime and nighttime propagation conditions. The U.S. Navy ELF Wisconsin Test Facility was the transmission source. The principal results obtained from these measurements were 1) the daytime attenuation rate is usually higher than the nighttime attenuation rate at both 45 and 75 Hz; 2) the relative excitation factors are quite different for daytime and nighttime propagation conditions; 3) nighttime propagation is more variable than daytime propagation; 4) there is a seasonal variation in the ELF propagation parameters; and 5) auroral-zone effects appear to be present at both frequencies.

I. INTRODUCTION

DURING July 1970 a two-site far-field extremely low frequency (ELF) propagation experiment was conducted in California and Hawaii [1]. Since that test, we have participated in three ELF propagation tests. For the first test (March–April 1971) [2], [3], the receiving sites were in the Virgin Islands, North Carolina, Utah, Nova Scotia, and Hawaii; for the second test (October–November 1971) [4], [5], the receiving sites were in Connecticut, Maine, Utah, Greenland, and Norway; for the third test (May 1972) [6], [7], the receiving sites were in Alaska, Greenland, Norway, Greece, and Saipan. Measurements have also been sporadically taken in Connecticut by the New London Laboratory since June 1970 [8]. The U.S. Navy ELF Wisconsin Test Facility (WTF) was the transmission source for all of these measurements.

At each location, the horizontal magnetic field strengths were measured at a band of frequencies centered at 45 Hz and 75 Hz. (The number and values chosen were to adequately represent one period of the standing wave [3], thus minimizing standing-wave effects.) An estimate of the field strength at each center frequency was obtained for each measurement site by averaging the absolute field strengths and weighting inversely according to frequency. Once this was done, the average attenuation rates and relative excitation factors were easily determined.

In this study, the results of these measurements will be discussed and compared with earlier results.

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II. THEORY

For distances sufficiently removed from the region of the antipode, the far-field horizontal magnetic field strength component (H_ϕ), produced by a horizontal electric dipole antenna located at the earth's surface, may be expressed as the sum of direct (DIR short-path) and "round-the-world" (R long-path) components. These components, which combine at each point to produce a standing-wave pattern, may be expressed as [9], [10]

$$|H_\phi|_{\mathrm{DIR}} \sim \frac{ILf}{240\pi}\left(\frac{2\pi\mu_0}{c}\right)^{1/2}\frac{\cos\phi}{h[\sigma_e(c/v)]^{1/2}}\frac{\exp(-\alpha\rho)}{(a\sin\rho/a)^{1/2}} \quad \text{A/m} \quad (1)$$

and

$$|H_\phi|_{\mathrm{R}} \sim \frac{ILf}{240\pi}\left(\frac{2\pi\mu_0}{c}\right)^{1/2}\frac{\cos\phi}{h[\sigma_e(c/v)]^{1/2}}\frac{\exp[-\alpha(2\pi a-\rho)]}{(a\sin\rho/a)^{1/2}} \quad \text{A/m} \quad (2)$$

where

- IL dipole moment of the transmitting antenna in ampere-meters;
- f frequency transmitted in hertz;
- ϕ azimuth angle in degrees;
- σ_e effective earth conductivity beneath transmitting antenna in mhos per meter;
- h effective ionospheric reflecting height in meters;
- v earth ionosphere waveguide phase velocity (typically $1.0 < c/v \leq 1.4$) in meters per second;
- α earth ionosphere waveguide attenuation rate in nepers per meter;
- ρ great-circle distance between source and receiver in meters;
- a radius of the earth (approximately 6.37×10^6 m).

If h is expressed in kilometers, ρ and a in megameters, and α in decibels per megameter, then $|H_\phi|_{\mathrm{DIR}}$ produced by the WTF antenna array (normalized with respect to the WTF east–west (EW) antenna ($L = 22.5$ km) at

$I = 300$ A) may be expressed as

$$20 \log_{10} |H_\phi|_{\text{DIR}} \sim K + 20 \log_{10} E_{\text{EW}} - \alpha\rho - 10 \log_{10} [a \sin(\rho/a)] + 20 \log_{10} \frac{F(\phi)}{B} \quad \text{dBAm}^1 \tag{3}$$

where

$$K = \begin{cases} -143.7 \text{ dB at 45 Hz} \\ -139.3 \text{ dB at 75 Hz,} \end{cases}$$

$F(\phi)/B$ is the WTF antenna pattern factor [11], and $E_{\text{EW}} = (h_{KM}(\sigma_{e\text{EW}})^{1/2}(c/v)^{1/2})^{-1}$ is defined as the relative excitation factor. E_{EW} should not be confused with zero-order mode earth-ionosphere waveguide excitation factor ($\Lambda_0 \sim 0.5$) [9], [10]. If E_{EW} is defined in the aforementioned manner, then, for a two-site measurement program, the only unknowns to be determined are α and E_{EW}.

III. RESULTS

From June 1970 to December 1972, horizontal magnetic field strength measurements were made sporadically in Connecticut [8] ($\rho \sim 1.6$ Mm). A summary of the normalized Connecticut field strength monthly averages with respect to the WTF EW antenna maximum value (i.e., $F(\phi)/B = 1$) is presented in Table I. Note that there is a seasonal variation in the measured field strengths. For instance, at 45 Hz, both the daytime and nighttime field strengths were approximately 2 to 3 dB higher during September 1970 and October/November 1971 than at other times. Furthermore, the 75-Hz daytime field strengths measured in 1970–1971 were approximately 1 dB higher than those measured in 1972; the 75-Hz nighttime field strengths measured in October 1971 were approximately 3 dB higher than those measured during October/November 1972. These differences are mostly due to changes in excitation factor rather than changes in attenuation rate. (At a range of 1.6 Mm, a 0.4-dB/Mm change in attenuation rate results in only a 0.6-dB change in field strength.)

During these tests, the Connecticut nighttime field strength exhibited much more variability than did the daytime field strength. On a few occasions (in particular, between October 28 and 31 for the past *four* years), the nighttime field strength was ~3 dB lower than on preceding or following nights. This nighttime field strength reduction (which has also been observed at other measurement locations [1], [4]) appears to be mainly due to a decrease in the nighttime excitation factor rather than to an increase in the nighttime attenuation rate.

A comparison of the predicted and measured horizontal magnetic field strengths for the March/April 1971 propagation test [2], [3] is presented in Table II. The agreement is excellent for both 45 and 75 Hz. The average daytime attenuation rates inferred from this test were 1.1 dB/Mm at 45 Hz and 1.5 dB/Mm at 75 Hz, whereas the average nighttime attenuation rates inferred from this test were 0.8 dB/Mm at 45 Hz and 0.96 dB/Mm at 75 Hz. The daytime relative excitation factor was about 3.5 dB greater than the nighttime relative excitation factor.

A comparison of the predicted and measured horizontal magnetic field strengths for the October/November 1971 propagation test [4], [5], [8] is presented in Table III. Again, the agreement is good at both frequencies. The average daytime attenuation rates inferred from this test were 0.9 dB/Mm at 45 Hz and 1.3 dB/Mm at 75 Hz, whereas the average nighttime attenuation rates were 0.9 dB/Mm at 45 Hz and 1.2 dB/Mm at 75 Hz. The daytime relative excitation factor was only about 1 dB greater than the nighttime relative excitation factor.

There are three major differences between the March/April and October/November 1971 measurements. First, the nighttime relative excitation factor has increased by approximately 2 dB over the intervening period. Second, the 75-Hz daytime relative excitation factor has decreased by approximately 1 dB. Third, the daytime attenuation rate has decreased by 0.2 dB/Mm at both frequencies, whereas the nighttime attenuation rate has increased by 0.1 dB/Mm at 45 Hz and 0.24 dB/Mm at 75 Hz.

TABLE I
1970–1972 CONNECTICUT MEASUREMENT RESULTS (ALL DATA NORMALIZED TO WTF EW ANTENNA AT 300 A)

Month	Frequency (Hz)	Monthly Average (dBAm)	Number of Measurement Days
9/70	45 day	−146.0	3
10/70		−148.0	2
11/70		−149.0	3
2/71		−148.0	6
3/71		−147.1	3
10/71		−146.0	7
11/71		−145.9	4
11/72		−148.3	1
12/72		−148.5	1
9/70	45 night	−147.8	4
10/70		−149.4	3
11/70		−149.5	3
12/70		−149.9	8
2/71		−149.9	3
10/71		−147.1	9
11/72		−149.1	5
6/70	75 day	−143.9	2
9/70		−143.6	4
12/70		−143.8	4
1/71		−143.8	4
10/71		−144.0	10
3/72		−144.8	2
7/72		−144.8	7
11/72		−145.1	2
12/72		−145.1	3
11/70	75 night	−147.0	2
1/71		−145.4	4
10/71		−144.8	11
10/72		−147.9	2
11/72		−147.1	3

[1] 1 dBAm = 1 dB/At/m.

TABLE II
MARCH/APRIL 1971 RESULTS (I = 300 A, Ψ = 0°, A = 0)

Frequency (Hz)	Location	Predicted H_ϕ Night (dBAm)	Measured H_ϕ Night (dBAm)	Predicted H_ϕ Day (dBAm)	Measured H_ϕ Day (dBAm)
45	North Carolina	−150.0	−149.9	−147.0	−147.3
	Virgin Islands	−155.0	−155.0	−152.7	−153.0
	Nova Scotia	−152.0	−152.0	−149.1	−148.8
	Utah	−152.6	−152.6	−149.7	−149.6
↓	Hawaii	−160.1	−160.0	−158.6	−158.6
75	North Carolina	−146.6	−146.4	−144.4	−144.3
	Virgin Islands	−152.1	−151.9	−151.0	−151.0
	Nova Scotia	−148.2	−148.3	−146.1	−146.1
	Utah	−148.7	−148.8	−146.6	−146.6
↓	Hawaii	−157.0	−157.0	−157.3	−157.3

45-Hz Prediction Assumptions: 1) α_D = 1.1 dB/Mm; α_N = 0.8 dB/Mm. 2) E_D = 1.15; E_N = 0.77. 3) E_D/E_N = 1.49.
75-Hz Prediction Assumptions: 1) α_D = 1.5 dB/Mm; α_N = 0.96 dB/Mm. 2) E_D = 1.04; E_N = 0.72. 3) E_D/E_N = 1.44.

TABLE III
OCTOBER/NOVEMBER 1971 RESULTS (I = 300 A, Ψ = 60°)

Frequency (Hz)	Location	Predicted H_ϕ Night (dBAm)	Measured H_ϕ Night (dBAm)	Predicted H_ϕ Day (dBAm)	Measured H_ϕ Day (dBAm)
45	North Carolina	—	—	−148.0	−147.8[a]
	Connecticut	−147.6	−147.6	−146.4	−146.4
	Maine	−147.0	−147.2	−145.7	−145.8
	Utah	−147.7	−147.1	−146.4	−146.2
	Greenland	−149.7	−149.7	−148.3	−148.5
↓	Norway	−154.3	−154.3	−153.0	−153.0
75	North Carolina	—	—	−146.0	−145.7[a]
	Connecticut	−144.5	−144.8	−143.7	−144.0
	Maine	−144.0	−143.9	−143.3	−143.0
	Utah	−144.8	−145.0	−144.1	−144.4
	Greenland	−147.8	−147.1	−147.2	−146.6
↓	Norway	−153.5	−153.3	−153.2	−153.1

[a] The Naval Underwater Systems Center/New London North Carolina results were taken in September 1971.
45-Hz Prediction Assumptions: 1) α_D = 0.9 dB/Mm; α_N = 0.9 dB/Mm. 2) E_D = 1.13; E_N = 0.99. 3) E_D/E_N = 1.15.
75-Hz Prediction Assumptions: 1) α_D = 1.3 dB/Mm; α_D = 1.2 dB/Mm. 2) E_D = 0.95; E_N = 0.85. 3) E_D/E_N = 1.12.

From November 29 to December 21, 1966 and from January 7 to February 4, 1967, ELF propagation measurements were made in Point au Feu, N. Y.; Goose Bay, Labrador; and Keflavik, Iceland [12]. The daytime and nighttime attenuation constants and relative excitation factors were determined by a least squares fitting of the data to (1). The 78-Hz attenuation rates were 1.01 dB/Mm for nighttime propagation and 1.29 dB/Mm for daytime propagation. A comparison of the October/November 1971 75-Hz and the 78-Hz attenuation rates results in excellent agreement for the daytime attenuation rate and fair agreement for the nighttime attenuation rate.

On the nights of October 28–29 and 29–30, 1971, the normalized (with respect to 45 Hz) 41-Hz nighttime field strengths measured in Connecticut, Maine, and Greenland were approximately 1.5 to 2.5 dB lower than the other nighttime field strengths measured during the October/November 1971 test period, whereas the Utah and Norway normalized nighttime field strengths were essentially the same. White [4] has hypothesized that these lower nighttime field strengths were caused by precipitating electron flux variations. One possible interpretation of these results is that both the nighttime attenuation rate and relative excitation factor were substantially decreased during these two nights (by ~0.6 dB/Mm and ~4 dB, respectively)!

The WTF transmitted a simple sinusoidal signal for two 8-h periods per day during both the March/April and October/November 1971 tests. For the May 1972 test, the WTF was operated for 24 h per day. During all of these measurements, either the Naval Underwater Systems Center [2] or Lincoln Laboratory [3] (or both) narrow-band ELF field intensity receivers were utilized.

For the May 1972 test [6], [7], the propagation paths from the WTF to each of the five sites were never in total darkness. A comparison of the predicted and measured daytime horizontal magnetic field strengths for the May 1972 propagation test is presented in Table IV.

The average 45-Hz daytime attenuation rate and relative excitation factor inferred from the Alaska/Saipan path results were 0.9 dB/Mm and 0.99, respectively. This interpretation, which can also be applied to the March 1971 Connecticut measurement results, is in fair

TABLE IV
MAY 1972 RESULTS (I = 300 A, Ψ = 120°)

Frequency (Hz)	Location	Predicted H_ϕ Day (dBAm)	Measured H_ϕ Day (dBAm)
45	Connecticut	−147.1	−147.1[a]
	Greenland	−149.9	−148.7
	Alaska	−149.6	−149.6
	Norway	−153.8	−154.3
	Greece	−159.8	−159.0
	Saipan	−159.0	−159.0
75	Connecticut	−144.5	−144.8[a]
	Greenland	−149.5	−147.1
	Alaska	−149.5	−149.5
	Norway	−155.2	−153.0
	Greece	−162.7	−160.1
	Saipan	−163.7	−163.7

[a] The Naval Underwater Systems Center/New London, Connecticut results are from March 1971 (45 Hz) and March and July 1972 (75 Hz).

45-Hz prediction assumptions: 1) α_D = 0.88 dB/Mm; E_D = 0.99 (Alaska/Saipan path).

75-Hz prediction assumptions: 1) α_D = 1.58 dB/Mm; E_D = 0.91 (Alaska/Saipan path).

agreement with the March/April 1971 daytime interpretations. (Both the average attenuation rate and relative excitation factor decreased.)

The average 45-Hz daytime attenuation rate inferred from the Wisconsin/Greece path is 0.8 dB/Mm. This inference is based upon the assumption that the daytime relative excitation factors are identical in Wisconsin, Connecticut, and Greece. This assumption should be valid since all three places are located at approximately the same latitude. It should be noted that because of 50-Hz power line interference, only three frequencies in the 45-Hz band could be adequately analyzed (as opposed to four in Norway and five in Alaska, Greenland, and Saipan).

The average 45-Hz daytime attenuation rate and relative excitation factor inferred from the Greenland/Norway path results were 1.5 dB/Mm and 1.44, respectively (which are 0.6 dB/Mm and 3.3 dB, respectively, *greater* than those inferred from the Alaska/Saipan path).

The average 75-Hz daytime attenuation rate and relative excitation factor inferred from the Alaska/Saipan path are 1.58 dB/Mm and 0.91, respectively. This interpretation, which can also be applied to the March and July 1972 Connecticut measurement results, is in good agreement with the March/April 1971 daytime interpretations. (The attenuation rate has increased by 0.1 dB/Mm, and the relative excitation factor has decreased by ~1 dB).

The measured 75-Hz daytime field strengths at the sites where the propagation path passed through the auroral zone (i.e., Greenland, Norway, and Greece) were approximately 2.5 dB higher than predicted using the Alaska/Saipan path values of attenuation rate and relative excitation factor. The average attenuation rate and relative excitation factor inferred from the Greenland/Norway path were 1.63 dB/Mm and 1.22, respectively.

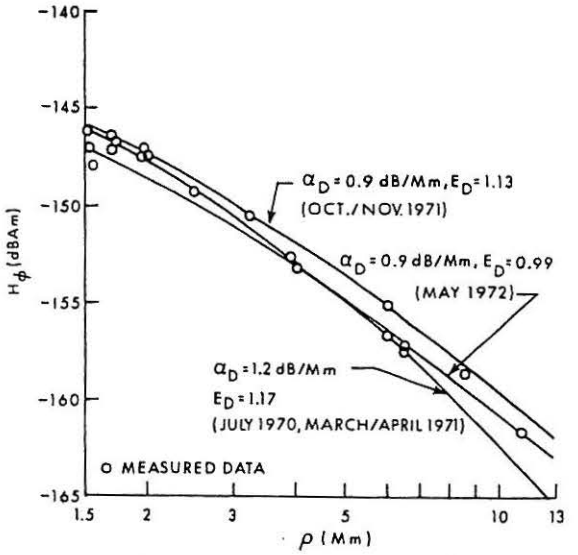


Fig. 1. Normalized H_ϕ component versus ρ, 45 Hz, daytime. Data normalized to WTF EW antenna at 300 A.

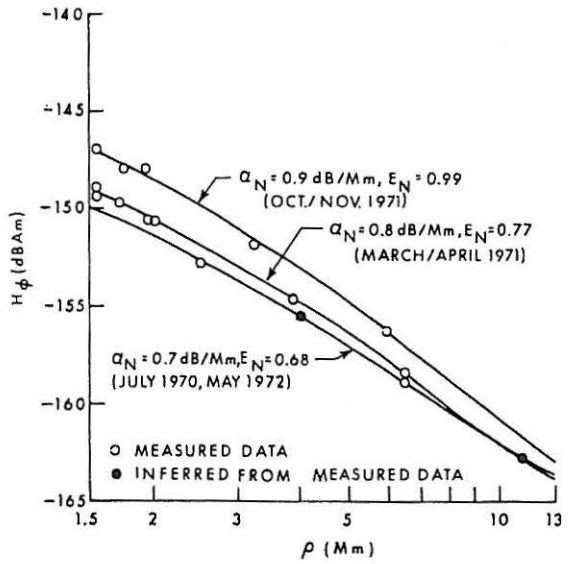


Fig. 2. Normalized H_ϕ component versus ρ, 45 Hz, nighttime. Data normalized to WTF EW antenna at 300 A.

The average attenuation rate inferred from the Wisconsin/Greece path is 1.29 dB/Mm (which is in excellent agreement with the October/November 1971 test 75-Hz result and the New York/Labrador/Iceland path 78-Hz result). Again, this inference is based upon the assumption that the daytime relative excitation factors are identical in Wisconsin, Connecticut, and Greece. Thus, it appears that this 45- and 75-Hz daytime change in attenuation rate and relative excitation factor is an auroral zone effect rather than a direction of propagation effect.

The normalized (with respect to the WTF EW antenna maximum value) far-field horizontal magnetic field strengths measured during these three joint tests are plotted versus range in Figs. 1 through 4. Also included are the July 1970 California/Hawaii results [1], the January 1972 Greenland/Norway results [4], and the 1970–1972 Connecticut measurements [8]. The WTF

TABLE V
WTF ANTENNA PATTERN FACTORS

Frequency (Hz)	Site Location	ρ (Mm)	ϕ_{NS} (degrees)	March–April 1971 Tests $\Psi = 0°, A = 0$ $F(\phi)/B$ (dB)	October–November 1971 Tests $\Psi = 60°$ $F(\phi)/B$ (dB)	May 1972 Tests $\Psi = 120°$ $F(\phi)/B$ (dB)
75	Connecticut	1.6	88.5	−0.2	0.0	—
	North Carolina	1.7	119.2	−0.5	−1.6	—
	Maine	1.8	66.6	—	+1.2	—
	Utah	2.0	−113.6	−1.6	+1.2	—
	Nova Scotia	2.0	72.2	−1.0	—	—
	Greenland	3.3	16.8	—	+1.7	+0.8
	Virgin Islands	3.9	119.3	−0.5	—	—
	Alaska	4.0	−58.0	—	—	+2.7
	Norway	6.0	10.0	—	+1.5	+1.5
	Hawaii	6.5	−108.7	−1.1	—	—
	Greece	8.6	33.0	—	—	−1.1
	Saipan	11.2	−68.8	—	—	+2.0
45	Connecticut	1.6	91.5	−0.3	−0.5	—
	North Carolina	1.7	122.2	−0.3	−1.6	—
	Maine	1.8	69.6	—	+0.8	—
	Utah	2.0	−110.6	−2.0	+0.8	—
	Nova Scotia	2.0	75.2	−1.4	—	—
	California	2.5	−103.4	−1.3	—	—
	Greenland	3.3	19.8	—	+2.1	+1.7
	Virgin Islands	3.9	122.3	−0.3	—	—
	Alaska	4.0	−55.0	—	—	+3.5
	Norway	6.0	13.0	—	+2.0	+2.4
	Hawaii	6.5	−105.7	−1.5	—	—
	Greece	8.6	36.0	—	—	−0.5
	Saipan	11.2	−65.8	—	—	+2.6

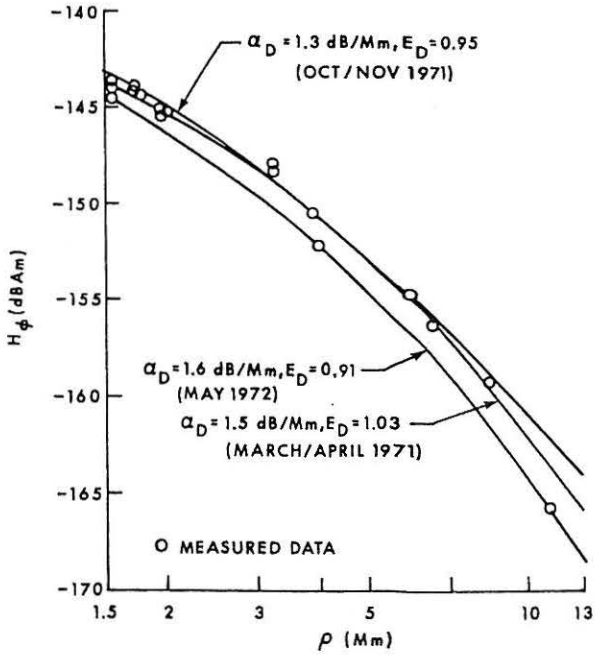


Fig. 3. Normalized H_ϕ component versus ρ, 75 Hz, daytime. Data normalized to WTF EW antenna at 300 A.

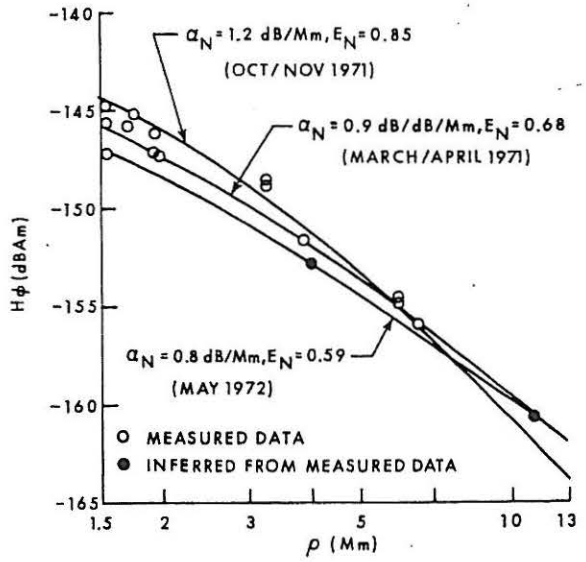


Fig. 4. Normalized H_ϕ component versus ρ, 75 Hz, nighttime. Data normalized to WTF EW antenna at 300 A.

antenna pattern factors used in the interpretation of these three joint tests are listed in Table V. These pattern factors are based upon the results of the August/September 1971 pattern and steering test [11]. From Figs. 1 through 4, it is observed that at the farther ranges the daytime horizontal magnetic field strengths are usually lower than the nighttime field strengths.

A comparison of the attenuation rates and relative excitation factors for various propagation paths is presented in Table VI. From this table, it is observed that the 45-Hz daytime attenuation rate variation for different paths is 0.3 dB/Mm (excluding auroral zone paths) and 0.7 dB/Mm (including auroral zone paths). The 45-Hz nighttime path variation is only 0.2 dB/Mm; at 75 Hz, the daytime path variation is 0.36 dB/Mm, while the nighttime path variation is 0.2 dB/Mm (excluding auroral zone paths) and 0.6 dB/Mm (including auroral zone paths). At both frequencies the nighttime relative excitation factors exhibit much more variation than do the

TABLE VI
COMPARISON OF PROPAGATION PATHS

Path	Date	Frequency (Hz)	α_D (dB/Mm)	E_D	h_D (km)[a]	α_N (dB/Mm)	E_N	h_N (km)[b]	E_D/E_N
California/Hawaii	July 1970	45	1.2	1.17	44.8	0.7	0.68	81.2	1.72
Utah/Hawaii	March/April 1971		1.2	1.17	44.8	0.8	0.77	71.7	1.53
North Carolina/Virgin Islands	March/April 1971		1.1	1.11	47.2	0.8	0.78	70.8	1.42
Greenland/Norway	October/November 1971		0.8	1.08	48.5	0.9	0.99	55.8	1.09
Greenland/Norway	May 1972		1.5	1.44	36.4	—	—	—	—
Alaska/Saipan	May 1972		0.9	0.99	52.9	0.7[c]	0.68[c]	81.2	1.45[c]
New York/Labrador/Iceland	November 1966–February 1967	78	1.29	—	—	1.0	—	—	1.15
Utah/Hawaii	March/April 1971	75	1.5	1.03	48.0	0.9	0.68	77.6	1.52
North Carolina/Virgin Islands	March/April 1971		1.55	1.05	47.0	1.0	0.74	71.4	1.43
Greenland/Norway	October/November 1971		1.52	1.11	44.5	1.4	1.00	52.8	1.11
Greenland/Norway	May 1972 (D), January 1972 (N)		1.63	1.22	40.5	1.4	1.05	50.3	—
Alaska/Saipan	May 1972		1.6	0.91	54.3	0.8[c]	0.59[c]	89.5	1.55[c]

[a] $h_D \sim 52.4/E_D$ km at 45 Hz and $49.4/E_D$ km at 75 Hz.
[b] $h_N \sim 55.2/E_N$ km at 45 Hz and $52.8/E_N$ km at 75 Hz.
[c] Inferred from measured data.

daytime relative excitation factors. Again, it appears that both frequencies are affected by auroral zone effects.

Once the effective earth conductivity beneath the WTF EW antenna and the waveguide phase velocities are known, the effective ionospheric reflecting height h can be obtained from the experimentally determined values of E_{EW}. The calculated results for h are also presented in Table VI. These calculations are based upon the measured values for σ_{eEW} of 2.8×10^{-4} mho/m at 45 Hz and 3.2×10^{-4} mho/m at 75 Hz [13]. The theoretical estimates of Galejs [14] for $(c/v)_D$ and the experimental values of Taylor and Sao [15] for $(c/v)_N$ have also been utilized. These c/v values also agree very well with the $\Delta(c/v) = (c/v)_D - (c/v)_N$ values measured during the May 1972 propagation test [6], [7] and the $(c/v)_D$ results determined from a combination of the WTF pattern measurement test [11] and the March/April 1971 propagation test [2], [3]. It should be noted that the results for h presented in Table VI are in excellent agreement with the theoretical predictions of Field [16], who stated that most of the ionospheric reflection must take place in the 40- to 60-km altitude range during the day and in the 50- to 90-km altitude range at night.

IV. SUMMARY

The principal results obtained during the past 3 years of ELF propagation measurements are as follows.

1) Seasonal changes in ionospheric characteristics that affect very low frequency (VLF) propagation also influence ELF propagation (i.e., both the attenuation rate and relative excitation factor change with season).

2) The daytime attenuation rate is higher than the nighttime attenuation rate at 75 Hz.

3) The daytime attenuation rate is usually higher than the nighttime attenuation rate at 45 Hz.

4) The daytime relative excitation factor is higher than the nighttime relative excitation factor at both 45 and 75 Hz.

5) ELF nighttime propagation is more variable than daytime propagation.

6) Auroral-zone effects appear to be present at both frequencies.

Because of the limited radiated power of the WTF (~0.25 W at 45 Hz and 0.5 W at 75 Hz), integration times of approximately 1.5 h per sample have been required at ranges >6 Mm in order to achieve a postdetection signal-to-noise ratio of 10 to 15 dB. In order to adequately study the short-term behavior of ELF propagation (employing integration times of ~15 min), a higher transmitter power will be required, particularly at the greater ranges.

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Resistivity Surveying as an Aid in Sanguine Site Selection

DAVID DAVIDSON, MEMBER, IEEE, DAVID N. MACKLIN, AND KEEVA VOZOFF

Abstract—A practical extremely low frequency (ELF) horizontal antenna requires a site of low effective conductivity. This paper describes the application of certain dc resistivity sounding methods in rapidly evaluating potentially useful areas within geologically interesting regions, and in determining both basement anisotropy and the direction of the principal (maximum) resistivity axis. Apparent resistivity data from dc array expansion is interpreted with a horizontal layered earth model using a "generalized inverse" method of fit. With layered models over principal axes the effective conductivity to be experienced with a horizontal wire antenna of arbitrary orientation is readily calculated. Salient results for three geographical regions are presented.

INTRODUCTION

RESISTIVITY surveying is an essential tool in selecting candidate extremely low frequency (ELF) antenna sites in areas known to possess basements of high resistivity rock. An inspection of the geological map of the USA reveals three outstanding areas: northern Wisconsin, northern New York state, and the Llano Uplift of Texas. Characteristic rock types include anorthosite, granite gneiss, gabbro, Precambrian igneous, and metamorphic rock.

Various techniques have been utilized by several groups to sample area resistivity properties, as well as to detail resistivity at specific locations. These techniques have included: 1) galvanic or dc surveying, using one or more well-known four-pole arrays; 2) H/I technique, measuring the remote horizontal H field due to a horizontal current over an element of the region; and 3) magnetotellurics, using natural fields, over the intended site. This paper discusses the exploitation of two dc array techniques in evaluating the potentially available area in a given region and in providing a detailed interpretation of the subsurface character at selected sites within the area so defined.[1]

A Wenner array is used for the reconnaissance investigation; with appropriate dimensions, the array yields apparent resistivities that determine whether the required skin depth can be met in the 40–50 Hz region. A fixed-dimension Wenner (we used 1000 m overall) is easily translated for rapid traverse. In the Llano Uplift region, for example, 51 Wenner measurements were made in a short period. The field results were paralleled with visual inspection of surface geology and checks with local geological maps.

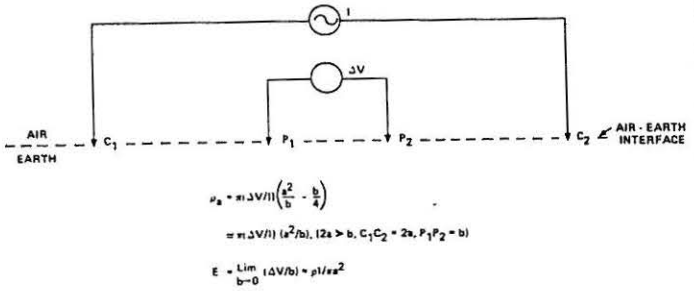


Fig. 1. Schlumberger array and the apparent resistivity ρ_a and electric field E when using it. (A Wenner array would have $b = 2a/3$.) Note: The essential information is contained in the electrode positions C_1, C_2, P_1, P_2.

SCHLUMBERGER ARRAY, ANISOTROPY, AND HORIZONTAL LAYERED MODELS

The Schlumberger array [1], used to study subsurface detail, has high sensitivity at long baseline lengths and, when expanded substantially, does not "see" the heterogeneities lying near the surface. In this sense, it is superior to dipole–dipole arrays and any induction method in assessing basement properties. Two traverses, preferably at right angles, were undertaken with a constantly expanding baseline, up to a length of 16 000 m. Generally, intersecting highways were convenient for this work, and care was taken to avoid close proximity to buried transmission lines or barbed-wire fences, Additionally, for each of the longer baselines, "skew" measurements were made whereby the potential-electrode baseline was rotated through at least three successive angles with respect to the current baseline. In-line expansion gives apparent resistivity as a function of baseline length (Fig. 1). If the earth is indeed stratified horizontally, there is a unique correspondence between the stratification and the apparent resistivity curve [2]. Historically, the stratified representation has been made by attempting to match the experimental curve with sets of master curves [1], [3]. Since this process has many pitfalls as detailed in the literature, the use of formal inversion techniques (already familiar in studies of the ionosphere) has become more and more prevalent, particularly with the advent of high-speed computational tools. In our investigation we used

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[1] For a review of techniques available for measuring earth conductivity see "Guide for methods of measuring earth conductivity," by the IEEE Wave Propagation Standards Committee, to be published soon in the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION.

a generalized inversion technique, introduced by Madden at M.I.T. and adapted for this case by Harter [4]. Madden's generalized inversion method has been used by Vozoff [5] to interpret audio magnetotelluric measurements made over sedimentary basins; it is a distinct advance over least-square methods.

The skew results permit locating the direction of the basement (dc) electric field; this direction is not collinear with the current if there is significant anisotropy (Fig. 2). This is because the surface potential due to a current source is a function of both polar coordinates, with apparent resistivity

$$[\rho_x\rho_y\rho_z/(\rho_x \cos^2\theta + \rho_y \sin^2\theta)]^{1/2} \qquad (1)$$

relative to principal axes.

DIRECTION OF THE ELECTRIC FIELD

The electric field for a Schlumberger array is approximated by measuring the potential with a potential (inner) baseline short compared to current (outer) baseline. The principal (minimum) conductivity (unknown) is along a direction γ; the direction of the current baseline is φ_I. The electric field always lies between γ and φ, along a direction β (Fig. 2). If three skewed potential baselines are used, the results are

$$u_i = \Delta V_i/l_i = (E_{||})_i \cos\alpha_i + (E_\perp)_i \sin\alpha_i, \quad i = 1,2,3 \quad (2)$$

where ΔV's are the potential differences, l_i the p-d baseline lengths, α_i the angles between successive p-d lines and the current baseline, and $(E_{||})_i, (E_\perp)_i$ the versions of the orthogonal field components obtained with each skew, where

$$E_{||} = |E| \cos\beta, \qquad E_\perp = |E| \sin\beta. \qquad (3)$$

Theoretically, only two values of $E_\perp$ and $E_{||}$ are needed. In our work, we used three to provide a consistency check. Averaging the results as $\bar{E}_{||}, \bar{E}_\perp$, we define the desired value of β via

$$\tan\bar{\beta} = \bar{E}_\perp/\bar{E}_{||}. \qquad (4)$$

Small field values will therefore affect the result least.

We then use a second position of the current baseline φ_{II}, usually nearly orthogonal to φ_I, and obtain two β's: $\bar{\beta}_I$ and $\bar{\beta}_{II}$. Denoting $R_{I,II} = \tan\beta_{I,II}$ for short, we find

$$\tan 2\gamma = \frac{\cos 2\varphi_I - \cos 2\varphi_{II} - (1/R_{II}) \sin 2\varphi_{II} + (1/R_I) \sin 2\varphi_I}{-\sin 2\varphi_I + \sin 2\varphi_{II} - (1/R_{II}) \cos 2\varphi_{II} + (1/R_I) \cos 2\varphi_I}. \qquad (5)$$

The index of anisotropy in the rock basement (skew measurements are always made with the long baselines) becomes for the two cases:

$$K_I, K_{II} = \cos 2\theta_{I,II} + (1/R_{I,II}) \sin 2\theta \qquad (6)$$

where

$$\theta_{I,II} = \varphi_{I,II} - \gamma$$

and

$$K_{I,II} = [(\sigma_x - \sigma_y)/(\sigma_x + \sigma_y)]_{I,II}.$$

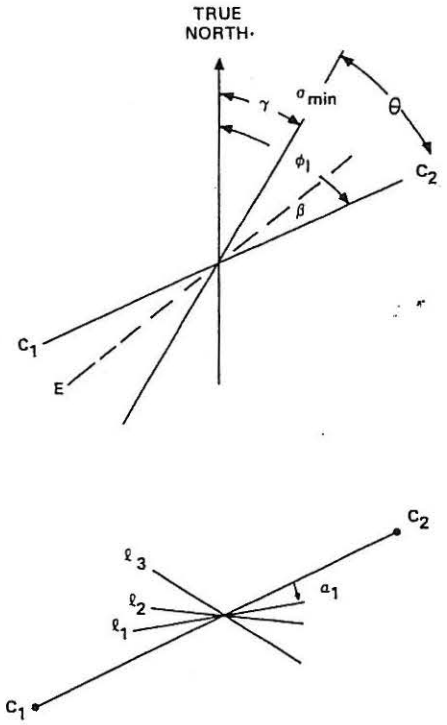


Fig. 2. Definition of essential angles for Schlumberger array relative to true north, to the minimum conductivity axis $(\sigma)_{min}$, and to the electric field E. Also, a depiction of skewed potential baselines.

Consistency can be checked by noting if $K_I = K_{II} = K$. If not, a range of possible values for K is established. Additionally, a third current baseline may be used to provide three values for K, and these can be weighted.

Since the in-line expansions originally chosen (for practical reasons) may not be along the principal axes, the expansion results for upper layers have to be rotated approximately to give layered modeling over the principal axes. Usually this is done by choosing the same model layer thicknesses on both axes but adjusting the resistivity ultimately in getting best fit. The stratification is always assigned to the nearer principal axes.

The ellipses represented by (1) lead to solutions for $\sigma_y\sigma_z = (1/\rho_y\rho_z)$ and $\sigma_z\sigma_z$. We cannot measure σ_z independently on the surface. However, since we deal with regions with aged crystalline rocks with almost entirely vertical fracturing, we can assume $\sigma_z \cong \sigma_y$. Then $\sigma_{min} = \sigma_z$, $\sigma_{max} = \sigma_y$.

TEST OF THE GENERALIZED INVERSE METHOD

The generalized inverse method was tested with synthetic data based on a known model and using various starting model assumptions. (See Table I.) The program

TABLE I
FIT OF THE GENERALIZED INVERSE METHOD USING CASE 1 STARTING MODEL AS "TRUTH"

CASE	REMARKS	STARTING ASSUMPTION ρ_a(Ω-m)	STARTING ASSUMPTION Δz(m)	COMPUTED END MODEL ρ_a(Ω-m)	COMPUTED END MODEL Δz(m)	MEAN ERROR ε
1	ρ_a - iteration	500	200	472	200	1.69
	3 - layers	2000	1000	1849	1000	
		8000		7711		
2	ρ_a - iteration	300	100	265	100	6.38
	3 - layers	3000	1500	1985	1500	
		10000		8438		
2A	ρ_a - iteration	300	100	484	204	1.4
	Δz - iteration	3000	1500	1716	863	
	3 - layers	10000		7546		
3	ρ_a - iteration	100	100	269	100	6.38
	3 - layers	1000	1500	1951	1500	
		3300		8486		
4	ρ_a - iteration	300	100	194	100	10.8
	± 10% data noise	3000	1500	3098	1500	
	3 - layers	10000		7025		
5	ρ_a - iteration	100	100	431	100	1.4
	6 - layers	300	200	729	200	
		2000	500	2148	500	
		4000	1000	2722	1000	
		6000	1500	13914	1500	
		10000		7120		
6	ρ_a - iteration	100	100	401	100	2.27
	± 10% data noise	300	200	620	200	
	6 - layers	2000	500	1639	500	
		4000	1000	21898	1000	
		6000	1500	5180	1500	
		10000		5540		
7	ρ_a - iteration	1000	100	436	100	1.4
	6 - layers	100	200	726	200	
		4000	500	2136	500	
		2000	1000	2709	1000	
		8000	1500	13832	1500	
		30000		7124		
8	ρ_a - iteration	1000	100		100	1.44
	6 - layers		200		00	
		1000	500	2132	500	
		1000	1000	2708	1000	
		1000	1500	14007	1500	
		1000		7096		

ΔZ = Layer thickness.
ρ_a = Layer resistivity.

can be operated in two "modes." In one, the assumed layers are fixed in thickness and only the resistivity is adjusted; in the other, both thickness and resistivity can be varied to achieve a fit. If the number of layers is overspecified, consolidation of neighboring layers of nearly the same resistivity will be indicated. For most of the survey final models having three, or at most four, layers were sufficient to achieve data fit. Comparison of Cases 1, 7, and 8 in Table I indicates the capabilities of the method.

It must be emphasized that in order to apply the layered model interpretation, the apparent resistivity obtained along roughly orthogonal directions must show some form of consistency. Gross departures on one axis from the curve on the other, or sharp changes with expansion may indicate large lateral discontinuities. The way in which these manifest themselves is shown in the monograph by Kunetz [6].

(While a horizontally stratified model is used, it is also possible to proceed with a similar development for stratification with vertical planes. Such a model would be used whenever the form of the expansion data along different axes suggests that vertical structuring is present.)

EFFECTIVE CONDUCTIVITY

The effective conductivity seen by a horizontal antenna of arbitrary orientation over each elementary surveyed region is determined by employing the dyadic representation of the resistivity properties, following Galejs [7]. Along any one principal axis, of course, the effective conductivity is calculated via Wait's "transmission line" formula [8], readily generalized to handle anisotropy.

Anisotropy is important if it is large, because there may be difficulty in securing the desired antenna pattern whatever orientation of antenna lines is chosen [7]. An antenna line at ELF of given length will perform most efficiently over the principal axis (minimum conductivity). If this happens to coincide with the direction of desired propagation, the designer is fortunate.

The question is often raised whether the earth "seen" at dc (or near dc, as in our case) is the same as is seen by waves at frequency ω. The surface impedance seen by a plane wave (interpretable also as a conductivity) has been developed by Wait [8] with a stratified model. If the elemental layers have uniform resistivity values then there is a one-to-one correspondence. Kunetz [9] shows the mathematical association between the impedance "transmission-line" formalism and the formula for the kernel of the Stefanesco integral [1] used to evaluate the apparent dc resistivity with a layered earth, in which an infinite set of images occurs.

TABLE II
NEW YORK ROCK TYPES AND RESISTIVITIES

Rock Type	Available Area (mi²)	Apparent dc Resistivity Range (Ω·m)
Anorthosite	1326	3800–8400
Granite Gneiss and Metasedimentary Rock	1071	5200–9300
Pyroxene Syenitic—Granite Gneiss	765	5300–14 600
Potsdam Sandstone	128	400–800
Mixed Gneisses and Gabbro	638	5000–15 000

RESULTS

The resistivity results of the dc survey in a candidate area are combined with values determined by others (though not necessarily at the same locations) to give an overall estimate of the potentially interesting area for Sanguine system purposes.

The Texas area comprises about 2000 mi² of known Precambrian igneous and metamorphic bedrock with also about 1000 mi² of Precambrian granite basement inferred from various geophysical and well data. There is good correlation between resistivities and distribution and age of rocks. At 40 Hz, there appears to be an available area of 1400 mi² with conductivity less than 4×10^{-4} mho/m.

At Marble Falls, Tex., a Schlumberger skew measurement revealed a basement anisotropy ratio of 1.5, while along Highway 29, the ratio was nearly unity. The minimum conductivity axis found at Marble Falls (bearing 69° TN) does parallel a known geologic fault.

For New York State, anisotropy ratio averaged 1.5 to 2, with largest values in metasedimentary areas. The available areas defined by rock type and associated apparent dc resistivities are listed in Table II.

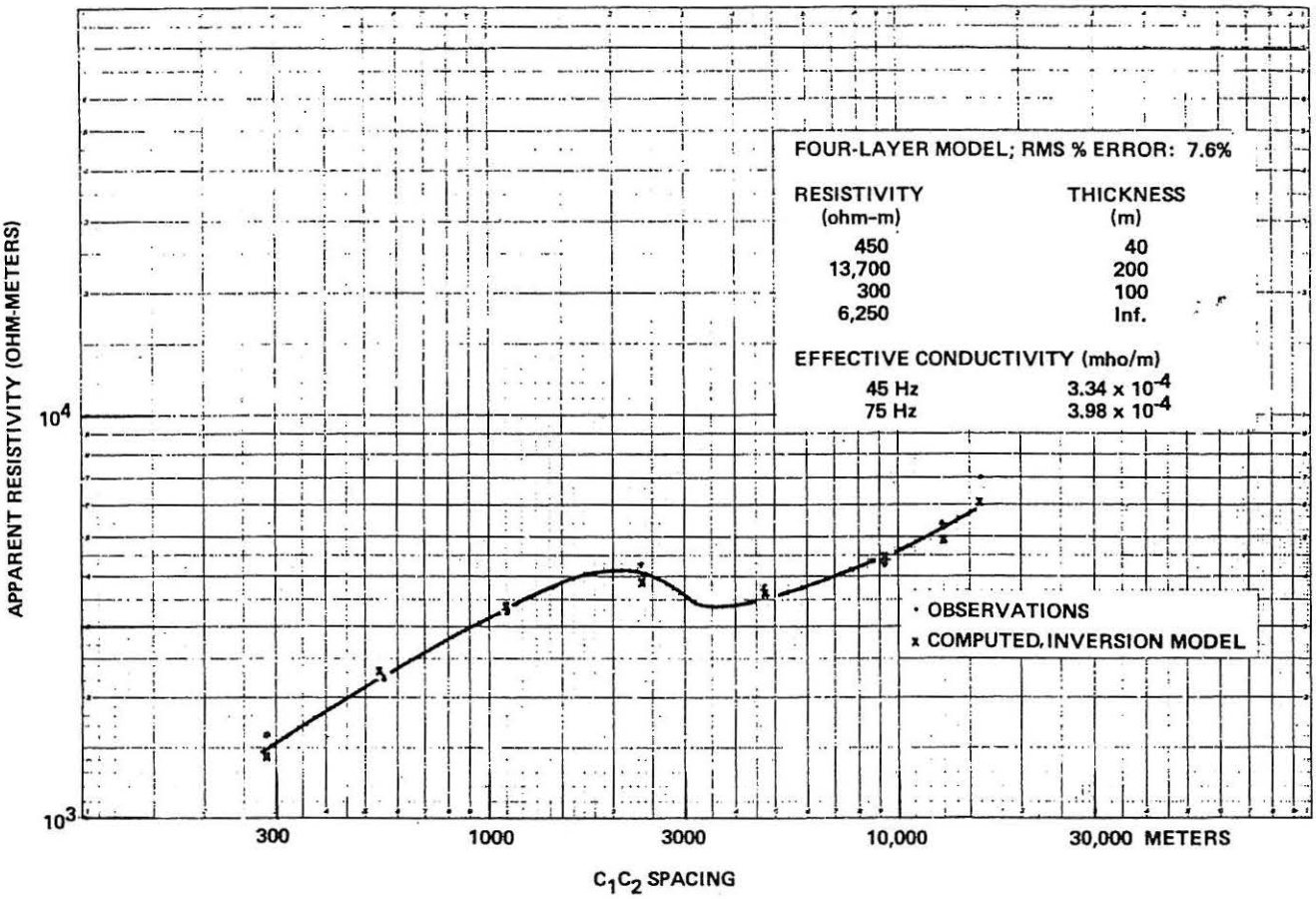


Fig. 3. Schlumberger data, obtained near the east line of the Wisconsin Test Facility, together with a layered model for the region obtained by the generalized inverse method, and the fit of points yielded by that model.

For the central portion of the Wisconsin Test Facility (WTF), a four-layer model was consistent with data from three separate Schlumberger expansions. Basement dc anisotropy was found to be 1.33. Though conductive the uppermost layer was so thin as to be ELF transparent. A significant conductive layer appears at about 300 m depth; it acts to condition the basement resistivities (8320/6250 Ω·m) as seen from the surface at ELF frequencies. The presence of this underlying stratum is consistent with inferences from geologic studies of the surrounding region. Fig. 3 gives the results for measurements about the east line of the WTF; this of course gives the north–south resistivity, see (1). It can be seen that a solid curve, based on the crosses representing points computed by the generalized inverse, is an excellent fit to the data.

(It should be mentioned that in the actual measurements reported here, commercial equipment operating between 0.1 and 3 Hz was employed to avoid electrode polarization effects.)

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Wisconsin Test Facility Transmitttng Antenna Pattern and Steering Measurements

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Abstract—During August and September 1971, the New London Laboratory, Naval Underwater Systems Center, performed pattern and steering measurements on the Wisconsin Test Facility (WTF) antennas. The pattern measurements were made at 13 locations in Minnesota and Wisconsin (covering approximately 120° of arc), while the far-field steering tests were taken in Maine and North Carolina. To be certain that the receiving sites were acceptable, several components of the received magnetic field were measured at each site and plotted on a normalized cosine curve. The 45- and 75-Hz pattern measurements were made at a range of approximately 300 km, while the steering measurements were performed at 1.7 Mm. The principal results from the pattern and steering measurements were 1) the east–west (EW) antenna pattern is skewed clockwise; 2) the north–south (NS) antenna pattern is skewed counterclockwise; and 3) the effective conductivity under the EW antenna is greater than the effective conductivity under the NS antenna.

I. INTRODUCTION

THE U.S. Navy Project Sanguine Wisconsin Test Facility (WTF) is located in the Chequamegon National Forest in north-central Wisconsin about 8 km south of the village of Clam Lake. This location was chosen because of its low electrical conductivity and sparse population. The facility was designed to test and demonstrate interference mitigation techniques and has also been used for ecological studies and as the source for extremely low frequency (ELF) propagation measurements.

The facility consists of two 22.5-km quasi-orthogonal antennas, with the transmitting station at the intersection near the midpoints of the antennas. Each antenna is grounded at both ends. It should be noted that the antenna lines are not straight. The average direction is 19° E of N for the north–south (NS) antenna and 109° for the east–west (EW) antenna. Although the WTF was designed for a maximum current of 540 A into each antenna, it has been operated to date at only 300 A, which is about one-third of its power output capacity.

During the fall and winter of 1970, the New London Laboratory, Naval Underwater Systems Center (NUSC/NL) performed ELF propagation measurements in Connecticut [1]. From these measurements, it was observed that both WTF antennas were skewed approximately 10° and that the effective conductivity under the EW antenna was greater than the effective conductivity under the NS antenna. Since it is necessary to know the antenna skews and their relative efficiencies in order to adequately interpret far-field ELF propagation measurements, we initiated a measurement program for their determination.

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II. PATTERN MEASUREMENT THEORY

For an end-grounded horizontal transmitting antenna (located over homogeneous isotropic earth), the maximum far-field radiation pattern will be in the direction of the antenna axis. However, in some instances, the maximum radiation pattern may be in some other direction. The difference in angle between the axis direction and the maximum radiation pattern direction is defined as the *pattern skew* or pattern skew angle.

The pattern skew of a horizontal electric transmitting antenna can be obtained by measuring two orthogonal horizontal magnetic field components (e.g., H_ρ and H_ϕ) at various distances and angles from the source. When the measurement distance is greater than approximately three ionospheric reflecting heights h from the source, H_ϕ and H_ρ may be expressed as [2],[3] (after some manipulation)

$$H_\phi \sim -\frac{i(IL)\cos\phi}{4(\omega\mu_0\sigma_e)^{1/2}h}(k^2)\left[H_0^{(2)}(kS_0\rho) - \frac{H_1^{(2)}(kS_0\rho)}{(kS_0\rho)}\right] \tag{1}$$

$$H_\rho \sim -\frac{i(IL)\sin\phi}{4(\omega\mu_0\sigma_e)^{1/2}h}(k^2)\frac{H_1^{(2)}(kS_0\rho)}{(kS_0\rho)} \tag{2}$$

where

- IL dipole moment of the transmitting antenna in ampere-meters;
- k $= \omega/c$;
- ϕ azimuth angle, in degrees, relative to the transmitting antenna axis;
- σ_e effective earth conductivity beneath the transmitting antenna in mhos per meter;
- μ_0 $= 4\pi \times 10^{-7}$ in henries per meter;
- S_0 earth-ionosphere waveguide propagation constant;
- h effective ionospheric reflecting height in meters;
- ρ great circle distance between source and receiver in meters.

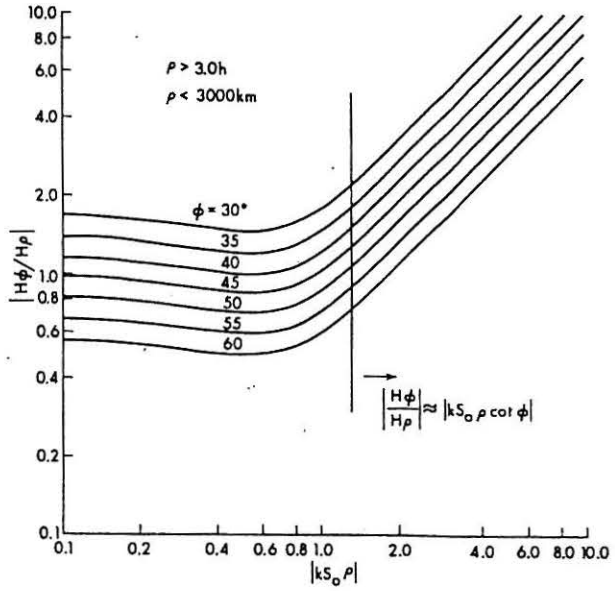


Fig. 1. $|H_\phi/H_\rho|$ versus $|kS_{0\rho}|$.

The ratio of H_ϕ to H_ρ is plotted in Fig. 1 versus the quantity $kS_{0\rho}$. For small values of $|kS_{0\rho}|$, $|H_\phi/H_\rho| \sim |\cot\phi|$, while for large values, $|H_\phi/H_\rho| \sim |kS_{0\rho}\cot\phi|$.

The range of 300 km was chosen for the pattern measurements (rather than a greater range) because of higher signal levels and ease of movement from site to site. For $\rho = 300$ km and $f = 45$ to 75 Hz, (1) and (2) may be rewritten as

$$H_\phi \sim -\frac{[IL/(\omega\mu_0)^{1/2}]\cos\phi K_2 \exp(-\alpha\rho)}{2\pi[h\sigma_e^{1/2}(c/v)^2]\rho^2} \quad (3)$$

and

$$H_\rho \sim \frac{[IL/(\omega\mu_0)^{1/2}]\sin\phi K_1 \exp(-\alpha\rho)}{2\pi[h\sigma_e^{1/2}(c/v)^2]\rho^2} \quad (4)$$

where K_1 and K_2 are slowly varying functions of f, S_0, and ρ

($20\log_{10}K_1 \simeq +0.7$ to 1.0 dB,
and $20\log_{10}K_2 \simeq -0.3$ dB)

and where $\alpha = -k\,\mathrm{Im}\,S_0$, the earth-ionosphere waveguide attenuation constant in nepers per m, and $v = c/\mathrm{Re}\,S_0$, the earth-ionosphere waveguide phase velocity in meters per second.

III. MEASUREMENT PROCEDURE

From August 16 to September 3, 1971, the WTF was operated at a current of 300 A (rms) for 8 h/day, 5 days/week. The EW antenna was energized in the mornings, the NS in the afternoons. The 45- and 75-Hz transmissions occurred on alternate days.

Two NUSC/NL field crews conducted the pattern measurements at 13 locations (covering 120° of arc) in southern Wisconsin and eastern Minnesota.

In order to be certain that the receiving sites were acceptable, many components of the received magnetic field were measured at each site (e.g., H_ϕ, H_ρ, $H_{max} = (H_\phi^2 + H_\rho^2)^{1/2}$, $H_{max} + 45°$, $H_{max} - 45°$, and H_z). The H_{max} component is linearly polarized, and its direction was calculated beforehand for 0° and 10° pattern skews. If the measured value of H_z was less than 20 dB down from H_{max}, (indicating that local anomalies were present), the site was discarded. The measured horizontal magnetic field components were then plotted on a receiving loop antenna figure-eight (i.e., cosine) pattern curve to determine if there were any other anomalies in the receiving antenna locations.

Receiving antenna location anomalies were discovered at some measurement locations in the Wisconsin/Minnesota area. Anomalies have also been noted at some far-field sites. This field experience regarding the effect of anomalous earth conditions suggests that an adequate checkout procedure for far-field propagation measurement sites be developed and employed.

During the pattern determination test, two NUSC/NL field intensity receivers were used by each measurement team. These receivers are described in detail in [4]. Integration times of 1 to 10 min per sample were employed for the majority of the measurements, resulting in approximately 3500 daytime samples.

IV. PATTERN MEASUREMENT RESULTS

Referring to (3) and (4), we see that by measuring the H_ϕ and H_ρ components produced by each WTF antenna (at a range of approximately 300 km), the following 45- and 75-Hz information can be obtained:

1) the pattern skew of the EW antenna;
2) the pattern skew of the NS antenna;
3) the parameter[1] $h_D(c/v)_D^2(\sigma_{e\mathrm{EW}})^{1/2}$ (once the skew of the EW antenna is determined);
4) the parameter $h_D(c/v)_D^2(\sigma_{e\mathrm{NS}})^{1/2}$ (once the skew of the NS antenna is determined);
5) the ratio of the effective conductivity under the EW antenna to the effective conductivity under the NS antenna (once both antenna skews have been determined);
6) since the 300-km (near-field) field strengths vary inversely as $h_D(c/v)_D^2\sigma_e^{1/2}$ and the far-field field strengths vary inversely as $h_D[(c/v)_D]^{1/2}\sigma_e^{1/2}$, the daytime phase velocity v may be determined from a combination of near-field and far-field measurements.

The measured [or determined from the receiving loop antenna pattern (figure eight) plots] and predicted values of H_ϕ, H_ρ, $|H_\phi/H_\rho|$, and H_{max} are listed in Tables I through IV. The predictions are based upon clockwise (CW) skews of 9° at 45 Hz and 5° at 75 Hz for the EW antenna and counterclockwise (CCW) skews of 8° at 45 Hz and 5° at 75 Hz for the NS antenna. A comparison of the measured and predicted results yields excellent agreement.

[1] D refers to daytime.

TABLE I
PREDICTED VERSUS MEASURED RESULTS: 45-Hz EW ANTENNA

Location	H_{max} (dBAm)**		H_ϕ (dBAm)		H_ρ (dBAm)		$\lvert H_\phi/H_\rho \rvert$ (dB)	
	Meas.	Predicted†	Meas.	Predicted	Meas.	Predicted	Meas.	Predicted
Wisconsin								
1. Rosiere	-127.0	-127.3	-127.0	-127.0	-149.0	-149.4	+22.0	+22.4
2. Morrison	-127.0	-127.1	-127.4	-127.3	-137.5	-138.0	+10.1	+10.7
3. Eldorado	-126.9	-126.9	-128.1	-127.9	-133.2	-132.9	+5.1	+5.0
4. Marquette	-126.4	-126.5	-128.8	-128.7	-130.5	-130.7	+1.7	+2.0
5. Portage	-126.7	-126.6	-129.4	-129.2	-130.2	-129.8	+0.8	+0.6
6. Loyd	-126.1	-126.2	-130.8	-130.8	-128.1	-128.1	-2.7	-2.7
7. Rising Sun	-125.9	-126.0	-133.6	-133.4	-126.9	-126.9	-6.7	-6.5
Minnesota								
8. Wilmington	-126.0	-125.9	-137.2	-137.3	-126.3	-126.2	-10.9	-11.1
9. Forestville	-125.9	-125.8	-147.1	-145.4	-126.0	-125.9	-21.1	-19.5
10. Hayfield	-125.6	-125.8	< -150.0	-152.6	-125.6	-125.8	< -24.0	-26.8
11. Havana	-125.7	-125.9	-142.0	-142.6	-125.8	-125.9	-16.2	-16.8
12. Elysian	-126.0	-126.0	-137.2	-136.7	-126.3	-126.3	-10.9	-10.4
13. New Auburn	-126.1	-126.2	-133.5	-133.1	-127.1	-127.0	-6.4	-6.1

* All data normalized to $I = 300$ A and $\rho = 300$ km.
† The predictions are based upon a 9° CW skew. $H_{\phi max} \simeq -127.0$ dBAm; $H_{\rho max} \simeq -125.8$ dBAm.
‡ 1 dBAm is 1 dB referred to 1 At/m.

TABLE II
PREDICTED VERSUS MEASURED RESULTS: 45-Hz NS ANTENNA

Location	H_{max} (dBAm)		H_ϕ (dBAm)		H_ρ (dBAm)		$\lvert H_\phi/H_\rho \rvert$ (dB)	
	Meas.	Predicted†	Meas.	Predicted	Meas.	P.	Meas.	Predicted
Wisconsin								
1. Rosiere	-123.4	-123.4	-133.7	-133.6	-123.9	-124.0	-9.8	-9.6
2. Morrison	-123.6	-123.6	-129.9	-130.3	-124.8	-124.8	-5.1	-5.5
3. Eldorado	-124.1	-123.9	-128.3	-127.9	-126.3	-126.2	-2.0	-1.7
4. Marquette	—	-124.1	—	-126.7	—	-127.5	—	+0.8
5. Portage	-124.1	-124.2	-126.0	-126.2	-128.4	-128.4	+2.4	+2.2
6. Loyd	-124.4	-124.6	-125.2	-125.3	-132.3	-131.6	+7.1	+6.3
7. Rising Sun	-124.8	-124.6	-125.1	-124.8	-137.9	-137.6	+12.8	+12.8
Minnesota								
8. Wilmington	-124.7	-124.7	-124.7	-124.6	<< -150	-160.5	>> +25	+35.9
9. Forestville	-124.6	-124.7	-124.8	-124.8	-139.0	-138.5	+14.2	+13.7
10. Hayfield	-124.5	-124.6	-125.1	-125.1	-133.2	-132.8	+8.1	+7.7
11. Havana	-124.4	-124.3	-125.8	-125.5	-130.0	-130.5	+4.2	+5.0
12. Elysian	-124.2	-124.1	-126.7	-126.4	-127.9	-127.9	+1.2	+1.5
13. New Auburn	-123.8	-123.9	-127.5	-127.8	-126.2	-126.2	-1.3	-1.6

* All data normalized to $I = 300$ A and $\rho = 300$ km.
† The predictions are based upon an 8° CCW skew. $H_{\phi max} \sim -124.6$ dBAm, $H_{\rho max} \sim -123.4$ dBAm.

TABLE III
PREDICTED VERSUS MEASURED RESULTS: 75-Hz EW ANTENNA

Location	H_{max} (dBAm)		H_ϕ (dBAm)		H_ρ (dBAm)		$\lvert H_\phi/H_\rho \rvert$ (dB)	
	Meas.	Predicted†	Meas.	Predicted	Meas.	Predicted	Meas.	Predicted
Wisconsin								
1. Rosiere	-129.0	-129.2	-129.2	-129.2	-145.0	-145.1	+15.8	+15.9
2. Morrison	-129.0	-129.1	-129.5	-129.5	-138.0	-138.0	+8.5	+8.5
3. Eldorado	-128.7	-128.8	-130.3	-130.4	-133.8	-133.7	+3.5	+3.3
4. Marquette	—	-128.7	—	-131.2	—	-131.9	—	+0.7
5. Portage	-128.5	-128.5	-131.9	-131.8	-130.9	-131.1	-1.0	-0.7
6. Loyd	-128.2	-128.2	-133.5	-133.7	-129.7	-129.6	-3.8	-4.0
7. Rising Sun	-128.1	-128.0	-136.7	-136.9	-128.7	-128.6	-8.0	-8.3
Minnesota								
8. Wilmington	-128.1	-127.9	-143.1	-141.5	-128.3	-128.1	-14.8	-13.4
9. Forestville	-127.8	-127.8	-148.9	-155.3	-127.8	-127.8	-21.1	-27.5
10. Hayfield	-127.8	-127.8	—	-147.4	-127.8	-127.9	—	-19.5
11. Havana	-127.8	-127.9	-141.5	-141.7	-127.9	-128.0	-13.6	-13.7
12. Elysian	-128.1	-128.0	-137.6	-137.2	-128.6	-128.5	-9.0	-8.7
13. New Auburn	-128.3	-128.2	-134.0	-134.2	-129.6	-129.4	-4.4	-4.8

* All data normalized to $I = 300$ A and $\rho = 300$ km.
† The predictions are based upon a 5° CW skew. $H_{\phi max} \sim -129.1$ dBAm; $H_{\rho max} \sim -127.8$ dBAm.

TABLE IV
PREDICTED VERSUS MEASURED RESULTS: 75-Hz NS ANTENNA

Location	H_{max} (dBAm)		H_ϕ (dBAm)		H_ρ (dBAm)		$\lvert H_\phi/H_\rho \rvert$ (dB)	
	Meas.	Predicted†	Meas.	Predicted	Meas.	Predicted	Meas.	Predicted
Wisconsin								
1. Rosiere	-126.2	-126.2	-137.4	-137.8	-126.5	-126.5	-10.9	-11.3
2. Morrison	-126.6	-126.6	-133.8	-134.0	-127.5	-127.2	-6.3	-6.8
3. Eldorado	-126.7	-126.7	-131.3	-131.2	-128.5	-128.6	-2.8	-2.6
4. Marquette	—	-126.8	—	-130.0	—	-129.7	—	-0.3
5. Portage	-127.0	-126.9	-129.5	-129.4	-130.5	-130.6	+1.0	+1.2
6. Loyd	-127.5	-127.3	-128.5	-128.5	-134.3	-133.4	+5.8	+4.9
7. Rising Sun	-127.4	-127.4	-127.8	-127.8	-138.4	-138.3	+10.6	+10.5
Minnesota								
8. Wilmington	-127.5	-127.5	-127.5	-127.5	-150.5	-149.8	+23.0	+22.3
9. Forestville	-127.6	-127.6	-127.7	-127.7	-145.1	-144.2	+17.4	+16.5
10. Hayfield	—	-127.4	—	-127.9	—	-136.8	—	+8.9
11. Havana	-126.8	-127.2	-128.0	-128.2	-133.3	-134.3	+5.3	+6.1
12. Elysian	-127.0	-127.0	-128.7	-129.0	-131.9	-131.5	+3.2	+2.5
13. New Auburn	-126.7	-126.7	-130.3	-130.3	-129.4	-129.4	-0.9	-0.9

* All data normalized to $I = 300$ A and $\rho = 300$ km.
† The predictions are based upon a 5° CCW skew. $H_{\phi max} \sim -127.5$ dBAm; $H_{\rho max} \sim -126.2$ dBAm.

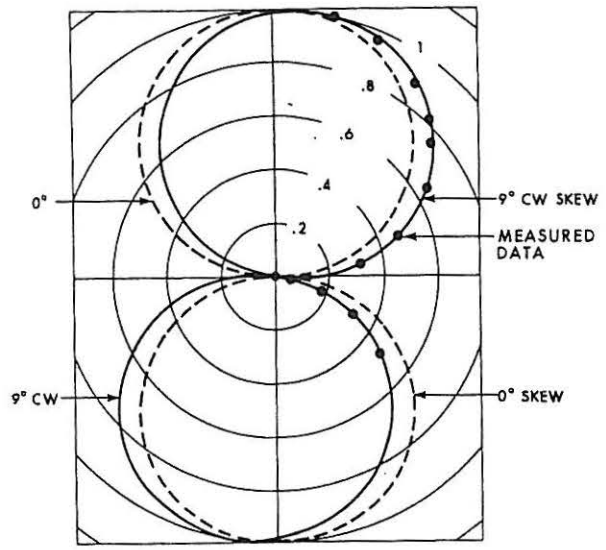


Fig. 2. H_ϕ versus cos ϕ: 45-Hz EW antenna.

TABLE V
SUMMARY OF PATTERN MEASUREMENT RESULTS

Parameter	45-Hz Result	75-Hz Result
EW Antenna Skew	9° ±1° CW	5° ±1° CW
NS Antenna Skew	8° ±1° CCW	5° ±1° CCW
Electrical Angle (θ, between WTF NS and EW Antennas	107° ±2°	100° ±2°
NS Antenna Electrical Location	11° ±1° E of N	14° ±1° E of N
EW Antenna Electrical Location	118° ±1° E of N	114° ±1° E of N
Ratio of NS Antenna Maximum to EW Antenna Maximum (A/B)	1.32 ±0.07	1.20 ±0.07
$\sigma_{eEW}/\sigma_{eNS}$	1.74 ±0.14	1.44 ±0.14
$h_D(c/v)^2\sqrt{\sigma_{EW}}$ (h in km)	1.32 ±0.04	1.30 ±0.04
$h_D(c/v)^2\sqrt{\sigma_{NS}}$ (h in km)	1.00 ±0.04	1.09 ±0.04
$(c/v)_D$ (Determined from pattern measurements and March-April 1971 propagation tests.)	1.31 ±0.05	1.23 ±0.05

Referring to (1) and (3), we see that the H_ϕ component produced by a horizontal electric transmitting antenna varies as cos ϕ. Presented in Fig. 2 is the 45-Hz EW transmitting antenna pattern plot for the H_ϕ component versus the azimuth angle ϕ, for 0° skew and the aforementioned skew. Note that the agreement is excellent. Similar plots of H_ϕ and H_ρ versus ϕ for both the EW and NS antennas (at both frequencies) also yield excellent agreement between the measured and aforementioned skews.

A summary of the pattern measurement results is presented in Table V. Included in this table are the aforementioned skews, the electrical angle θ between the WTF antennas, and the antenna electrical locations. *Electrical location* is defined as the sum of the antenna axis angle and the pattern skew angle (e.g., at 75 Hz, the EW antenna axis direction is 109° E of N and the pattern skew is 5° CW; therefore, the electrical location of this antenna is 114° E of N.) The *electrical angle* between the antennas is defined as the difference in electrical location between them. Table V also includes the ratios of the NS antenna maximum value to the EW antenna maximum value (A/B), $\sigma_{eEW}/\sigma_{eNS}$, $h_D(c/v)^2(\sigma_{eEW})^{1/2}$, $h_D(c/v)_D^2(\sigma_{eNS})^{1/2}$, and $(c/v)_D$. The daytime phase velocity values have been determined from a combination of the pattern measurement tests and the March/April 1971 far-field propagation measurement results [4],[5].

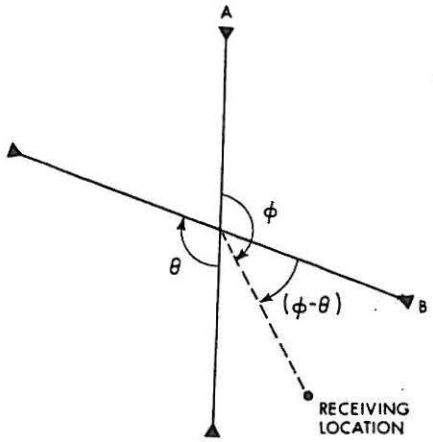


Fig. 3. Nonorthogonal array diagram.

V. STEERING TEST RESULTS

Once the EW and NS antenna patterns and their relative efficiencies have been determined, the array pattern may be predictably steered to any location. Referring to Fig. 3, we see that the steered pattern factor $F(\phi)$ for the H_ϕ component produced by a nonorthogonal array composed of two horizontal electric transmitting antennas may be expressed as

$$F(\phi) = A \cos \phi + B \cos (\phi - \theta) \exp (j\Psi) \qquad (5)$$

where

- ϕ azimuth angle with respect to the NS antenna;
- θ electrical angle between the NS and EW antennas;
- Ψ phasing angle between the antennas;
- A maximum field strength produced by the NS antenna;
- B maximum field strength produced by the EW antenna.

Referring to (3) or (4), we note that

$$\frac{A}{B} = \frac{I_{NS}L_{NS}}{I_{EW}L_{EW}} \left(\frac{\sigma_{eEW}}{\sigma_{eNS}}\right)^{1/2}. \qquad (6)$$

Thus, when both antennas are of equal length and current, $A/B = (\sigma_{eEW}/\sigma_{eNS})^{1/2}$.

The magnitude of $F(\phi)$ may be written as

$$|F(\phi)| = [A^2 \cos^2 \phi + 2AB \cos \phi \cos (\phi - \theta) \cos \Psi + B^2 \cos^2 (\phi - \theta)]^{1/2}. \qquad (7)$$

TABLE VI
MAINE/NORTH CAROLINA STEERING TEST RESULTS

Swansboro, North Carolina					Mars Hill, Maine				
Frequency (Hz)	Phasing (deg)	A/B, θ	Predicted Pattern Gain (dB)	Measured Pattern Gain (dB)	Frequency (Hz)	Phasing (deg)	A/B, θ	Predicted Pattern Gain (dB)	Measured Pattern Gain (dB)
75	0	1.20,	-8.8	-8.4	75	0	1.20,	+2.4	+2.3
	58.9	100°	-1.8	-1.7		58.9	100°	+1.3	+1.1
	78.4		-0.2	+0.2		120		-2.8	-2.6
	120		+2.5	+2.2		180		-9.0	-8.7
	180		+3.7	+3.3					
45	0	1.32,	-11.4	-11.9	45	0	1.32,	+2.0	+2.3
	57.2	107°	-1.6	-1.5		57.2	107°	+0.9	+0.6
	120		+3.2	+3.5		120		-3.2	-3.5
	180		+4.4	+4.3		180		-9.6	-9.3
						120		+4.2*	+4.5*
						180		+5.3*	+5.0*

* Pattern gains for H_ρ component.

If $A = B = 1$ and $\Psi = 180° - \theta$, then $F(\phi) = \sin\theta$. For this case, $F(\phi)$ is independent of ϕ, and an omnidirectional pattern with a normalized amplitude of $\sin\theta$ is realized. To determine the pattern factor for the H_ρ component produced by a nonorthogonal array composed of two horizontal electric transmitting antennas, simply substitute $(\phi - \pi/2)$ for ϕ in (5) and (7).

If the EW antenna is used as the reference for defining the WTF antenna pattern factor, then (7) becomes

$$\left|\frac{F(\phi)}{B}\right| = \frac{A}{B}\left[\cos^2\phi + \frac{2\cos\phi\cos(\phi-\theta)\cos\Psi}{(A/B)} + \frac{\cos^2(\phi-\theta)}{(A/B)^2}\right]^{1/2}. \quad (8)$$

Various values of $F(\phi)/B$ (with $B = 1$) versus the receiving location bearing (with respect to true north) are plotted in Fig. 4 for 45 Hz. The values of θ and A/B employed are taken from the pattern measurement results (Table V).

Referring to (8) and Fig. 4, we see that the maximum field strength produced at any single location is realized when $\Psi = 0$ or π. Furthermore, when $(\phi - \theta) \simeq \pi/2$ or $3\pi/2$ (e.g., Norway),

$$\left|\frac{F(\phi)}{B}\right| \sim \frac{A}{B}\cos\phi \quad (9)$$

and when $\phi \simeq \pi/2$ or $3\pi/2$ (e.g., Connecticut),

$$\left|\frac{F(\phi)}{B}\right| \sim \cos(\phi - \theta). \quad (10)$$

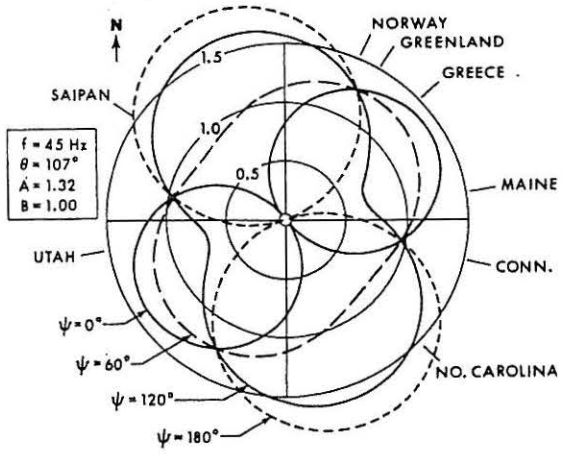


Fig. 4. $F(\phi)/B$ versus receiving location bearing: 45 Hz.

From September 20 to 24, 1971, a far-field steering test was conducted at two 1.7 Mm sites, Swansboro, N.C., and Mars Hill, Me. Four different phasings were used at 45 Hz, and five at 75 Hz. Here again, the measured pattern gains (with respect to the EW antenna maximum field strength B) and the predicted gains (which are based upon the pattern test results) presented in Table VI agree extremely well.

VI. SUMMARY

The principal results from the daytime August and September 1971 WTF pattern and steering measurements are the following.

1) The EW antenna is skewed 9° ± 1° CW at 45 Hz and 5° ± 1° CW at 75 Hz. The electrical location of the EW antenna is 118° ± 1° E of N at 45 Hz and 114° ± 1° E of N at 75 Hz.

2) The NS antenna is skewed at 8° ± 1° CCW at 45 Hz and 5° ± 1° CCW at 75 Hz. The electrical location of the NS antenna is 11° ± 1° E of N at 45 Hz and 14° ± 1° E of N at 75 Hz.

3) The electrical angle θ between the NS and EW antennas is 107° ± 2° at 45 Hz and 100° ± 2° at 75 Hz.

4) The ratio of the maximum field strength produced by the NS antenna to that produced by the EW antenna (A/B) is 1.32 ± 0.07 at 45 Hz and 1.20 ± 0.07 at 75 Hz. Therefore, the ratio of $\sigma_{e\mathrm{EW}}$ to $\sigma_{e\mathrm{NS}}$ is 1.74 ± 0.14 at 45 Hz and 1.44 ± 0.14 at 75 Hz.

5) The daytime values for the parameter $h_{KM}(c/v)^2 \cdot (\sigma_{e\mathrm{EW}})^{1/2}$ are 1.32 ± 0.04 at 45 Hz and 1.30 ± 0.04 at 75 Hz, while the daytime values for the parameter $h_{KM}(c/v)^2(\sigma_{e\mathrm{NS}})^{1/2}$ are 1.00 ± 0.04 at 45 Hz and 1.09 ± 0.04 at 75 Hz.

6) A combination of the pattern measurement results with the March/April 1971 propagation test results yields values of $(c/v)_D$ equal to 1.31 ± 0.05 at 45 Hz and 1.23 ± 0.05 at 75 Hz.

Inasmuch as the NS and EW antennas are skewed in different directions and the effective conductivity under each antenna is different, the WTF area either is anisotropic or is characterized by near-surface inhomogeneities (for further details, see [6]).

A listing of the measured magnetic field strengths at each location, the number of samples taken, and the standard deviation of the measured data is given in [7].

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Nighttime Variations of Extremely Low Frequency (ELF) Signal Strengths in Connecticut

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Abstract—A limited amount of extremely low frequency (ELF) horizontal magnetic field strength measurements have been taken in Connecticut during the past 3 years. The transmission source for these 1.6 Mm range measurements was the U. S. Navy ELF Wisconsin Test Facility. The principal result obtained from these measurements is that there are considerable variations in the ELF nighttime propagation parameters.

INTRODUCTION

DURING the past 3 years (June 1970–May 1973) we have sporadically made extremely low frequency (ELF) horizontal magnetic field strength measurements in Connecticut. Prior to October 1971, the local measurement site was located in the Nehantic State Forest, East Lyme. Since that time, it has been located in Hammonassett State Park, Madison. Each of these sites is at least 1 km (in any direction) from power and telephone lines.

The transmission source for these 1.6 Mm range measurements was the U. S. Navy ELF Wisconsin Test Facility (WTF), which is located in the Chequamegon National Forest in north-central Wisconsin—about 8 km south of the village of Clam Lake.

During these measurements, the Connecticut nighttime field strength exhibited much more variability than did the daytime field strength. (For further details see [1].) On a few occasions (in particular, during the nights of October 29, November 6, and November 23, 1970; October 28 and October 29, 1971; October 31, 1972; and April 19 and May 14, 1973), the nighttime field strength was approximately 2–5 dB lower than on preceding or proceeding nights. This nighttime field strength reduction has been observed at various frequencies and at other measurement locations [2]. It appears to be due mainly to a decrease in the nighttime excitation factor rather than to an increase in the nighttime attenuation rate. (At a range of 1.6 Mm, a 0.4 dB/Mm change in attenuation rate is only a 0.6 dB change in field strength.) White [2] has hypothesized that these lower nighttime field strengths are caused by precipitating electron flux variations. Gough and Collin [3] have found a clear correlation between particle flux and magnetic activity K_p summed over 24 h for 13 rockets launched from South Uist, Northern Scotland. Their measurements showed that precipitating energetic electrons become a dominant source of the nighttime D-region on 15 $\pm$ 11 percent of the nights at solar minimum to 35 $\pm$ 20 percent at solar maximum.

It is the purpose of this paper to present specific examples of ELF nighttime field strength variations.

EXAMPLES OF ELF NIGHTTIME VARIABILITY

A sample-by-sample plot of the nighttime field strength measured during the period of October 30 through November 4, 1972 is presented in Fig. 1. (The integration time per sample is 32 min.) The average 75 Hz field strength for the nights of November 1–4 was −147.1 dBAm.[1] On October 30, the nighttime field strength started out at this level, increased from 2130–2230 to −145 dBAm, and then steadily decreased to a level of ∼ −149 dBAm at 0100 on October 31. The nighttime field strength remained at this level until about 2200 and then began to increase. During the next night, the measured field strengths returned to their normal level.

[1] dBAm = dB re 1 ampere-turn per meter.

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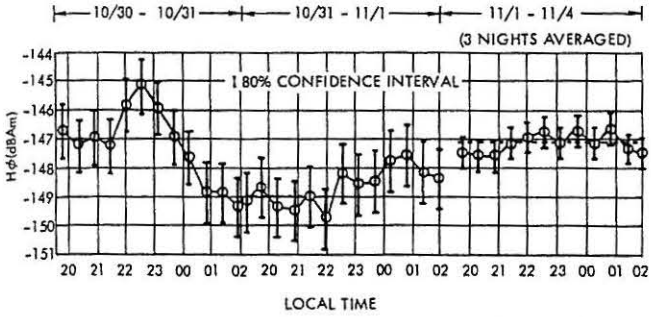


Fig. 1. October–November 1972 Connecticut 75 Hz nighttime field strengths versus local time.

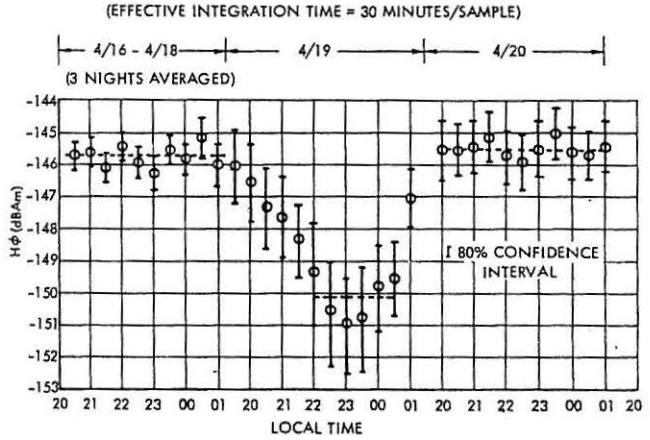


Fig. 2. April 16–20, 1973 Connecticut 76 Hz nighttime field strengths versus local time.

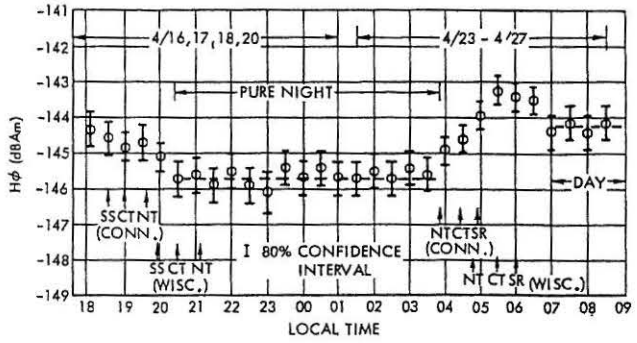


Fig. 3. April 16–27, 1973 Connecticut 76 Hz field strengths versus local time.

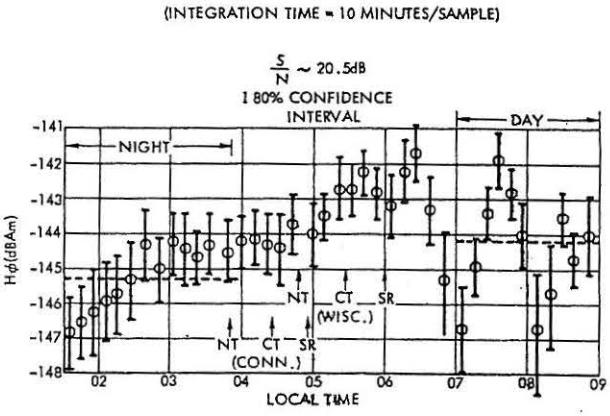


Fig. 4. April 25, 1973 Connecticut 76 Hz field strengths versus local time.

A solar proton event took place from October 29 to November 5, 1972 [4]. At 2100 on October 30, the proton flux (21–70 MeV) peaked at 50 times the preevent level and did not return to the preevent level until midnight on October 31. Thus, there appears to be a correlation between ionospheric irregularities and the lower than normal measured nighttime field strengths.

A sample-by-sample of the 76 Hz nighttime field strengths measured during the period of April 16–20, 1973 is presented in Fig. 2. (The effective integration time per sample is 30 min.) The average 76 Hz field strength for the nights of April 16–18 was −145.7 dBAm. On April 19, the nighttime field strength started out at about this level, then rapidly decreased to a minimum of −151 dBAm at 2300. The field strength then began to increase and reached a level of −147 dBAm when the transmitter went off the air. During the next night, the measured field strengths returned to their normal level.

The 76 Hz magnetic field strength 30 min averages measured during the period of April 16–20 (excluding 19 April) and April 23–27, 1973 are plotted versus local time in Fig. 3. The WTF east–west (EW) antenna transmitted at 300 A (rms) from 1800-0130 EST during the week of April 16–20 and from 0130–0900 EST during the week of April 23–27.

Referring to Fig. 1, we see that the average nighttime field strengths are fairly consistent from sample to sample (as are the average daytime field strengths). Note that the daytime period does not start until about an hour after Wisconsin sunrise. Possibly this is because the ionospheric C-layer ($\sim$ 40–60 km) was not fully developed until that time. It is within this layer that most daytime ELF reflections take place [5],[6].

The 76 Hz magnetic field strength 10 min integration time samples for April 25, 1973 are plotted in Fig. 4. The average S/N was 20.5 dB, which was the highest (after 10 min of integration time) of any night during the April measurement period [1]. The field strength started out at a low level (−146.8 dBAm), steadily increased till about 0630 EST, and then oscillated between −141.7 and −146.7 dBAm from 0630–0900 EST. Despite these oscillations, the average daytime field strength was the same as during the rest of the week (±0.2 dB).

The 10 min integration time average field strengths measured from May 14–18, 1973 are presented in Fig. 5, whereas the 30 min effective integration time daily results are plotted in Fig. 6. (Each 30 min effective integration time sample is an average of three 10 min integration time samples.) Note that the May nighttime field strengths are much more variable than those measured in April. The average May nighttime field strengths were also

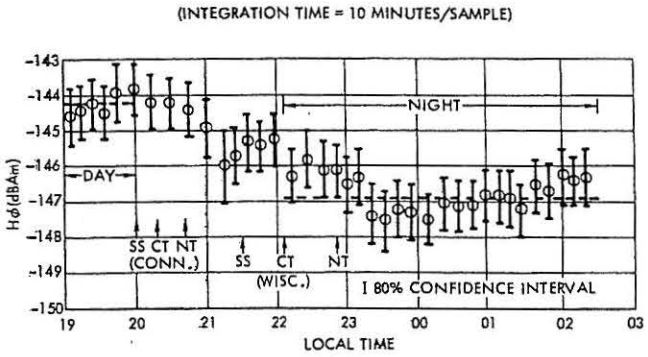


Fig. 5. May 14–18, 1973 Connecticut 76 Hz field strengths versus local time.

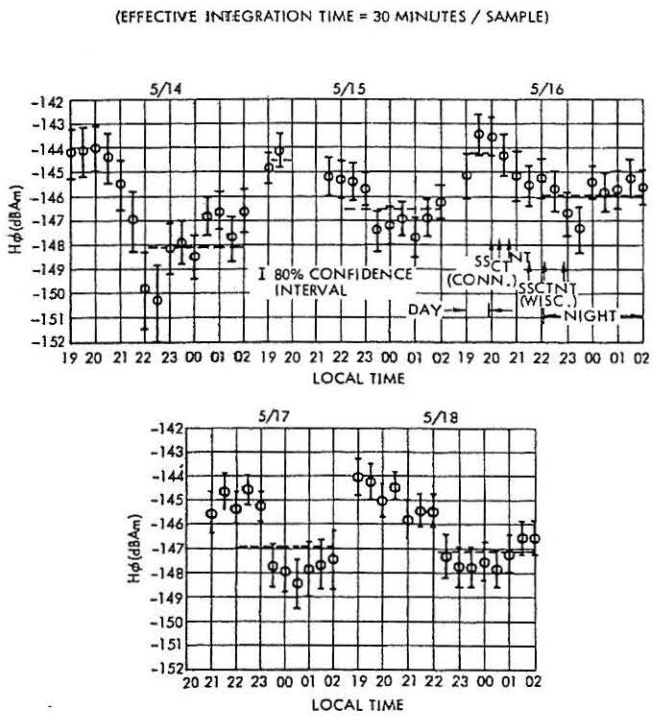


Fig. 6. Daily comparisons of the May 14–18, 1973 Connecticut 76 Hz field strengths.

lower by about 1 dB, whereas the average daytime field strengths were about the same (±0.2 dB).

On May 14 the levels started out at the normal daytime level, then rapidly decreased during the sunset transition period. Then they slowly increased and reached the average May nighttime level around 0030 EDT.

Referring to Fig. 3, we see that in April nighttime propagation began at about ½ h after Wisconsin sunset (at Civil Twilight). In May (Figs. 5 and 6), it appears that nighttime propagation did not begin until about 1½ h after Wisconsin sunset (at Nautical Twilight). [The average field strength measured during the period between Civil and Nautical Twilight was about 1 dB higher than measured after Nautical Twilight (~ 2300 EDT).]

CONCLUSION

The limited amount of horizontal magnetic field strength measurements taken in Connecticut during the past 3 years has demonstrated that there are substantial variations in the ELF nighttime propagation parameters. On a few occasions, the nighttime field strength was approximately 2–5 dB lower than on preceding or proceeding nights. This nighttime field strength reduction has been observed at various frequencies and at other measurement locations. It appears to be due mainly to a decrease in the nighttime excitation factor rather than to an increase in the nighttime attenuation rate. There also appears to be a correlation between ionospheric irregularities and these lower than normal measured nighttime field strengths.

In the future, the Connecticut site will be utilized more frequently than in the past. Thus, the data base will be expanded considerably. Short integration times (~ 30 min whenever possible) will be employed in order to further study short-term ELF propagation variations.

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Peter R. Bannister (M'69), for a photograph and biography, see this issue, page 418.

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Frederick J. Williams, for a photograph and biography, see this issue, page 418.

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J. Robert Katan (S'62–M'66), for a photograph and biography, see this issue, page 421.

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The Influence of Certain Ionospheric Phenomena on Extremely Low Frequency (ELF) Propagation

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Abstract—**A number of phenomena that may cause irregularities in extremely low frequency (ELF) ionospheric propagation are suggested. Geomagnetic anisotropy, path asymmetry due to different ionospheric characteristics on the darkened and sunlit hemispheres, effects of strong boundary discontinuities such as the twilight zone or northern latitude sporadic *E*, and the effects of geophysical trauma such as solar particle fluxes are considered.**

A primitive analysis of ELF propagation data illustrates that an association can be drawn between the effects of solar charged particle emissions and coincident ELF propagation irregularities. Paths that pass through the auroral zone appear to be most severely affected.

I. INTRODUCTION

THE purpose of this paper is twofold: 1) to apply current knowledge of extremely low frequency (ELF) propagation theory and results of experiment to forecast the types of ionospheric phenomena that may have an impact upon ELF communications,[1] and 2) to discern as much as possible regarding these influences from the small amount of measurement data acquired to date in Project Sanguine.

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[1] A review of ELF propagation investigations, which forms the basis for these forecasts, has been circulated by Davis *et al.* [1], in the format of a technical report. This material should be consulted for greater detail.

Section II describes the ionospheric phenomena that are most likely to have a significant effect upon ELF communications. Section III contains a primitive interpretation of the few examples of experimental data that indicate the impact of ionospheric phenomena.

II. PROBLEM AREAS OF INTEREST FOR RESEARCH

Several possible irregularities and anisotropies of propagation are suggested by Davis *et al.* [1]. Table I lists four prominent categories into which such degrading phenomena may be grouped, and twelve subcategories either of specific physical mechanisms, or of the consequences of such mechanisms (some of which are somewhat redundant), which may be conveniently isolated for theoretical study.

The items listed in the first category, Bidirectional Propagation, are of importance because the low attenuation constants expected at ELF should permit energy from both the direct (short great circle) and antipodal (long great circle) paths to propagate to much of the world. The spatial interference pattern that results may cause thousands-of-kilometers-scale wave field fluctuations of 3 to 6 dB at ranges beyond 7000 to 10 000 km. As an example of the degree to which the bidirectional characteristics of ELF propagation may affect received wave fields, a simple calculation has been carried out based

TABLE I
PROBLEM AREAS FOR ELF PROPAGATION RESEARCH

Bidirectional Propagation
1) Geomagnetic nonreciprocity
2) Day–night asymmetry
3) Transequatorial paths
Multilayer Resonance Effects
1) Anomalous high attenuation
2) Dispersion
Ionospheric Discontinuities
1) Height changes at twilight zone
2) Interposed conducting layers such as sporadic E
3) Solar and nuclear perturbations
Northern Latitude Phenomena
1) Solar X-ray flares
2) Solar charged particle fluxes
3) PCA events
4) Magnetic storms

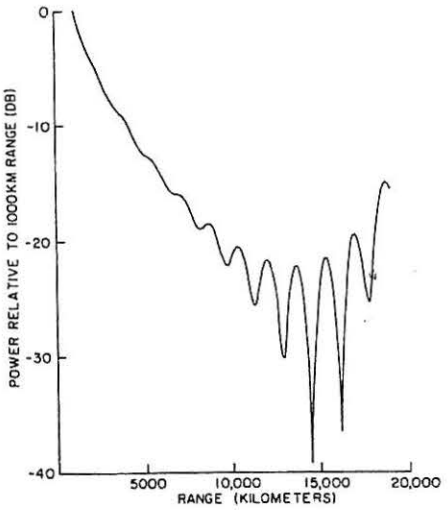


Fig. 1. Far-field azimuthal magnetic field component at 75 Hz. Short-path attenuation rate is 50 percent higher than long-path attenuation rate as estimate of combined geomagnetic and day–night asymmetry.

upon the "Wait model" described by White and Willim [2].

Fig. 1 shows the far-field azimuthal component of the 75-Hz magnetic field (H_φ) relative to its value at 1000 km from the transmitter. The wave-field profile is extended to 19 000 km, beyond which antipodal effects make the far-field expression invalid. The 75-Hz transmitter is assumed to be located 2000 km from the twilight zone and in the darkened hemisphere. Transmission in the main propagating mode across the twlight zone is assumed to be complete, an expedient which probably causes field strengths to be over estimated. The ranges shown on the horizontal scale are measured from the twilight zone and in the sunlit hemisphere. Attenuation in the darkened hemisphere (which is assumed here to coincide with an easterly long-great-circle path) is assumed to be 1.0 dB/1000 km. Attenuation in the sunlit hemisphere (a westerly short-great-circle path) is assumed to be 1.5 dB/1000 km. These values represent the most disparate 75-Hz results reported by White and Willim [2] and can be considered as an indication of the reasonable extreme of both day–night and geomagnetic path asymmetry. Notice that bidirectional effects are significant (deeper than 3 dB) beyond 7000 km.

Other examples of path asymmetry should be investigated. Unpublished experimental work by Hughes (discussed by Davis *et al.* [1]) suggests that dark paths crossing the equatorial zone display unexpected characteristics.

The second category, Multilayer Resonance Effects, may arise because the extremely long wavelengths characteristic of ELF waves allow energy to penetrate tens to hundreds of kilometers above the nighttime D and lower E regions. The existence of higher layers then can cause standing waves to be set up which may create absorption maxima in certain frequency bands of a few hertz width. This matter was first discussed by Galejs [3] and later refined [4] to indicate that for realistic midlatitude E- and F-layer ionospheric models they can be expected to yield effects on attenuation rate of the order of a few tenths of a decibel per 1000 km. The entire region of the ionosphere above the D layer is expected to influence ELF propagation under dark path conditions, however. Hence the phenomena whose effects must be investigated include not only the nighttime F layer, but additional nocturnal ionospheric effects such as northern latitude sporadic E. As will be seen in the following paragraphs, it is likely that essentially no ELF wave energy penetrates such a sporadic-E layer, and the condition described by Galejs [3] may occur for standing waves between the D region and this type of layer.

The items listed under the category Ionospheric Discontinuities in Table I involve primarily local wave-field irregularities which may occur due to mode conversion within a few hundred to a thousand kilometers of the three sources of ionospheric boundary height changes indicated. Height changes of about 20 km will be encountered at the twilight zone, for example, and may create a modal interference pattern in this transition region which will greatly complicate communications to receivers located within it. In the work reported by White and Willim [2] and Bannister [5], however, the integration time of 1.4 h and longer precluded detection of twilight zone effects (and furthermore, as indicated by White and Willim [2], they were deliberately avoided in most measurements). Interposed conducting layers of thousands of kilometers extent, such as sporadic E, can be expected to cause equally degrading effects when they occur on an ELF transmission path at night. During nighttime, ELF wave fields penetrate well above the D layer and hence may be highly susceptible to such occurrences. This possibility is of substantial concern



Fig. 2. Locations of possible communications link propagation paths relative to arctic auroral zone and polar cap.

because both the equatorial and auroral zones are subject to frequent occurrence of sporadic E.

Northern Latitude Phenomena, the fourth category listed in Table I, include the ionospheric effects associated with solar activity such as X-ray-induced charged particle concentrations in the D and lower E regions and similar sudden changes in ionospheric composition caused by the electron and proton flux bursts that often follow solar eruptions. Polar cap absorption (PCA) events are extreme manifestations of such occurrences. As an example of the importance of such phenomena, whose effects are often most pronounced in the auroral regions, Fig. 2 is an azimuthal equidistant, projection centered in the northeastern United States and showing a possible transmitter location in northern Wisconsin. The fan-shaped area indicates paths to probable regions of operational communications interest (great circles through the transmitter are approximately straight lines). Also indicated on Fig. 2 are three somewhat irregularly shaped rings centered on the northern magnetic pole in the vicinity of Ellesmere Island. These rings bound the northern auroral zone and polar cap, and it is evident that all propagation paths of interest pass through this region for a distance of several thousand kilometers. Northern latitude phenomena that affect the auroral region lower ionosphere thus must be investigated carefully.

As an illustration of the extent to which northern latitude sporadic E can be expected to affect ELF propagation at a frequency of 75 Hz, Fig. 3 contains curves of apparent wavelength (free-space wavelength divided by

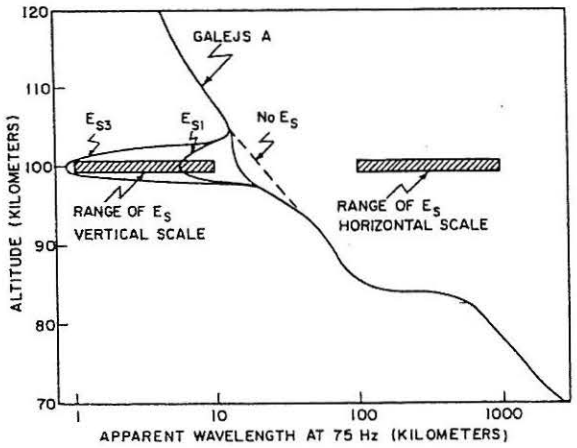


Fig. 3. Apparent electromagnetic wavelength versus altitude for ELF waves of 75 Hz.

the real part of the refractive index) versus altitude for typical ionospheric electron density profiles at this frequency.

The solid curve labeled "Galejs A" is representative of typical nighttime electron density profiles and was used for some of the Galejs calculations [3]. This curve contains a small contribution from sporadic E, and the dashed curve segment labeled "No E_S" illustrates the condition that exists in the complete absence of sporadic E. The two protuberances labeled "E_{S1}" and "E_{S3}" indicate the modifications to this curve which are introduced by moderate (E_{S1}) to strong (E_{S3}) nighttime sporadic E in the 100-km region of altitude. These modifications result in a compression of the apparent wavelength of 75-Hz propagating waves into the 1- to 10-km scale interval. The crosshatched areas represent typical horizontal and vertical scale sizes for sporadic E at 100-km altitude. Even under a condition of moderate sporadic E, it is evident that such a layer displays a vertical extent comparable to an apparent wavelength at 75 Hz, and hence a sporadic-E layer must be considered to be of considerable influence upon ELF propagation.

The polar ionosphere experiences an extensive variation for the period of up to several days following a strong solar flare, due to energetic solar electrons and protons that impinge upon the lower ionosphere during such a period. At ELF, this phenomenon is of great influence because it produces intense ionization throughout the D and E regions above about 60° geomagnetic latitude (nominally the auroral zone and polar cap). Most of the added ionization is produced in the 40–80-km altitude region. Field [6] calculated ELF attenuation rates including the effects of ion density enhancement in the lower D region in addition to the electron density increase. He showed that low-altitude ions associated with a PCA event increase ELF attenuation rates in the daytime. Observations [7] indicate that the electron density below about 70 km following a PCA event is almost completely removed at sunset. The behavior of the negative ions following such an event is not known, but their influence on ELF propagation may be pronounced.

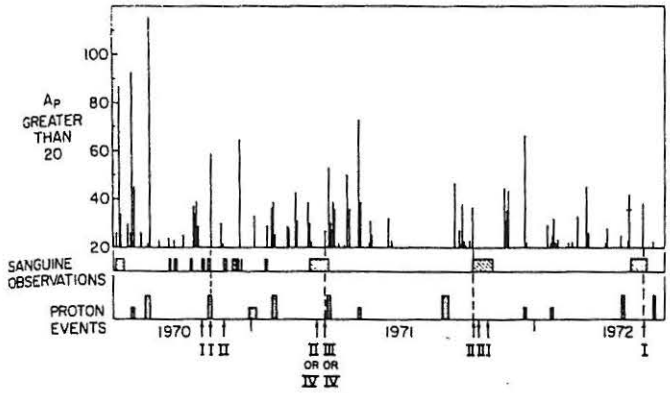


Fig. 4. Solar proton activity, geomagnetic activity, and Sanguine propagation measurement periods.

III. SANGUINE PROPAGATION MEASUREMENT RESULTS

A. Circumstances of the Observations

With the present relatively low-power Sanguine transmitter, only a very limited investigation into relatively short-term effects such as twilight-zone phenomena, or long-path effects such as bidirectional propagation, can be conducted. The major questions involving day–night or east–west asymmetry of propagation must remain unanswered until higher power is available, and such short-lived solar/geophysical phenomena as solar X-ray flares have not been accessible to study. It has been possible to confirm that ionospheric phenomena of the type described in the fourth category in Table I, Northern Latitude Phenomena, do have an impact upon ELF propagation, although it has not been possible to establish a cause–effect relationship between specific solar impetus and ionospheric response. The remainder of this paper will be devoted to a case-study interpretation of the few data that appear to indicate the effect of ionospheric disturbance on Sanguine test transmissions.

As White and Willim [2] indicate, Sanguine propagation tests have encountered the unfortunate circumstance that all measurements have been conducted during periods of relative ionospheric quiescence. Fig. 4 contains an indication of the solar activity during the period from mid-1970 to the end of 1972 in which Sanguine measurements have been made. The four 2-week periods reported by White and Willim [2] and Bannister [5] are indicated by crosshatched areas labeled "Sanguine observations," together with a number of brief intervals in late 1970 and early 1971 in which a number of observations were made in Connecticut and Massachusetts (largely in preparation for the field trips reported in [2], [5]). Above the bottom line are indicated the intervals described as "solar proton events" by the U. S. Department of Commerce Environmental Data Service (tall bars), and periods of lesser but significant solar proton emission (half-height bars). As an indication of the earthly manifestations of solar charged particle activity, the top line contains a bar graph of all periods of geomagnetic activity in which

TABLE II
ELF Signal/Geophysical Activity Classifications

Class	ELF Signal Behavior	Geophysical Conditions
I	pronounced anomaly	probable associated disturbance
II	pronounced anomaly	no obvious disturbance
III	marginal anomaly	probable associated disturbance
IV	marginal anomaly	no obvious disturbance

the magnetic index A_p exceeded 20. This classification includes all major magnetic storms and most moderate ones as well. The four vertical dashed lines between graphed parameters indicate the only four occasions in which it was indicated that substantial ionospheric disturbance coincided with Sanguine observations. Along the bottom of Fig. 4 are indicated nine periods, each designated by a Roman numeral I to IV, which will be discussed in the following paragraphs. The Roman numerals represent a crude classification system that has been applied to the Sanguine measurements made during each of those nine intervals and the degree of geophysical activity which existed at the time. Table II defines the classification system.

Four of the cases indicated in Fig. 4 fall under the Class I condition in which there is a probable geophysical association with observed signal irregularities. These cases will be discussed in detail. The remaining cases include four in which pronounced anomalous ELF signal behavior coincided with no apparent strong geophysical disturbance (Class II) and, hence, in which more obscure ionospheric phenomena must be investigated. Their full explanation will require an extensive series of observations and analysis. The remaining case involves less pronounced anomalous ELF signal behavior and less obvious ionospheric disturbance and will not be treated in detail. During July 1970 the signal-to-noise-ratio of ELF data was too poor to permit even a crude analysis of ionospheric disturbance effects to be made, and so those data are excluded from this accounting.

The observed ELF signal anomalies are of two types. As indicated by White and Willim [2], measured values of signal-to-noise ratio can be used to determine a statistical confidence interval within which a prescribed fraction of measured signal data should fall. (The 80-percent confidence interval described by White and Willim [2] will be maintained in this paper for convenience.) During some periods the observed data from one or several receiving sites display either a variability in excess of the expected degree (i.e., fewer than 80 percent of the samples fall within the 80-percent confidence interval) or the mean signal level for that period falls well outside the expected interval when compared to data acquired under similar conditions in different time periods. Examples of both such types will be discussed.

B. Specific Examples

This primitive analysis is based on data described by White and Willim [2] and Bannister [5]. The four most

prominent examples of anomalous behavior in the ELF signal occurred in October and November of the years 1970–1972. In all four cases, the signal level normally observed at all receiving sites dropped from one day to the next by several increments of its 80-percent confidence interval, remained low for one to two days, and then regained its earlier level. These four examples (plus a less pronounced one in May 1972) will be discussed as follows, followed by a brief presentation of the other examples.

1) *October* 1970: For receivers in Connecticut and Massachusetts, between the Local Standard hours of 2100 and 0130 on the nights beginning October 29 and 30, 1970, mean signal levels in Connecticut (10 samples) were depressed below the normal mean of −155.4 dB relative to 1 A/m·$\sqrt{\text{Hz}}$ (henceforth designated dBH) by 7.1 dB and 3.8 dB, respectively. With an estimated signal-to-noise ratio of 15 dB per sample, the 80 percent confidence interval for these mean data (see White and Willim [2]) is approximately 1.2 dB, and thus the disturbance is quite a pronounced one. Data acquired in Massachusetts on October 29, 1970 indicated a depression on that date of 4.9 dB below the normal mean field strength of −155.0 dBH with a signal-to-noise ratio of 18 dB (80 percent confidence interval of 2.3 dB). No data were obtained in Massachusetts on October 30. The Connecticut data were also quite variable on these two nights, with many sample-to-sample fluctuations outside the 80-percent confidence interval of 3.9 dB for individual samples. Some of the observed levels these nights were in excess of 15 dB below the mean nighttime value. A sampling interval of 34 min was used for these data. Daytime measurements on October 30 showed no significant departures either from normal field strengths or from expected sample-to-sample variation.

During the period October 28 to 30, 1970, a number of solar flares occurred, and solar X-ray flux in the 1–8-Å wavelength interval, which is of importance for lower ionosphere charged particle behavior, was disturbed. Sudden ionospheric disturbances (SID's) occurred also during this period and were accompanied by sudden cosmic noise absorption (SCNA) events. Such events normally indicate the arrival of charged particles (protons) from the sun, leading to increases in lower ionospheric charged particle density and enhanced absorption of cosmic radio waves. A decrease in galactic cosmic ray flux (a Forbush decrease [8]) also occurred on October 28, 1970, with effects lasting several days. Such behavior normally coincides with the onset of a magnetic storm or substorm and signals the effect upon the earth of the charged particles emitted by the sun in such a disturbance.

2) *November* 1970: The Connecticut site was operated on the nights of November 6 and 7, 1970 with a transmitted frequency of 75 Hz. The observed mean signal level decreased from a value on November 5, 1970 of −151.4 dBH, the normal level for nighttime reception of 75 Hz at this site, to a value of −154.7 dBH the following night. The 80-percent confidence interval for these data was less than 1 dB, and so the variation is significant. Coincident with the signal decrease between these two dates was the occurrence of a solar proton event which began November 5, 1970. Associated with this occurrence were satellite-measured energetic proton fluxes which peaked at midday on November 7, 1970 and a Forbush decrease which began at 0400 GMT and peaked at 1900 GMT November 7 with a 7-percent depressed level. A magnetic storm commenced early November 7 and reached a maximum A_p of 58 and maximum horizontal magnetic field strength variation in the auroral zone at College, Alaska, of 2320 γ.[2]

3) *October–November* 1971: The ELF signal response was equally pronounced in this case. Fig. 5(a) is a plot of nighttime data in the 45-Hz band acquired in Connecticut, Maine, Utah, Greenland, and Norway, between October 25 and November 3, 1971. The Connecticut data were taken with a sampling interval that was much shorter than the other four graphs, and individual samples could not be distinguished on the scale of this plot. Accordingly, only the nightly mean signal level is plotted for Connecticut. For the other four sites, the data are shown as irregular line segments connecting individual samples, with the nightly mean values indicated by a heavy line through the data of all 10 nights. Indicated along the abscissa are the transmission frequencies used each night, and to the right of each site's data is a bracketed line segment indicating the 80-percent confidence interval for nightly mean data. An unmistakable signal anomaly commences at the top four sites on October 29, 1971 and persists into the following night. The signal-to-noise ratios were nearly equal at these four sites, and so the disturbances on the easterly paths are quite pronounced, involving a night-to-night change of six to seven times the 80-percent confidence interval. The Norway data are less consistent, but nevertheless indicate large departures from normal conditions and from the expected variability. Daytime data for the same sites are shown in Fig. 5(b). The variations from day-to-day are less striking than in Fig. 5(a), but (with the exception of Connecticut) are significant and consistent with the general trend of nighttime data. It should be noted as well that the sites on the auroral segment of the path (Greenland and Norway) frequently show similar short-term behavior. The trend of samples on the nights of October 31, 1971 through November 3, 1971 are examples of this common behavior, in contradistinction to that of the Connecticut and Utah data for these nights. Trends in the daytime data of Fig. 5(b) are not so obvious, but the large sudden signal level changes at the auroral stations on October 29 and November 3 suggest that profound short-term phenomena certainly do occur on the auroral zone segment of the path. It should be noted, incidentally, that changes of transmitting frequency from day to day during any of the measurements described here should not be suspected as introducing bidirectional propagation effects. For the

[2] The geomagnetic variations are described in conventional geophysical units. One γ is equal to 10^{-5} T.

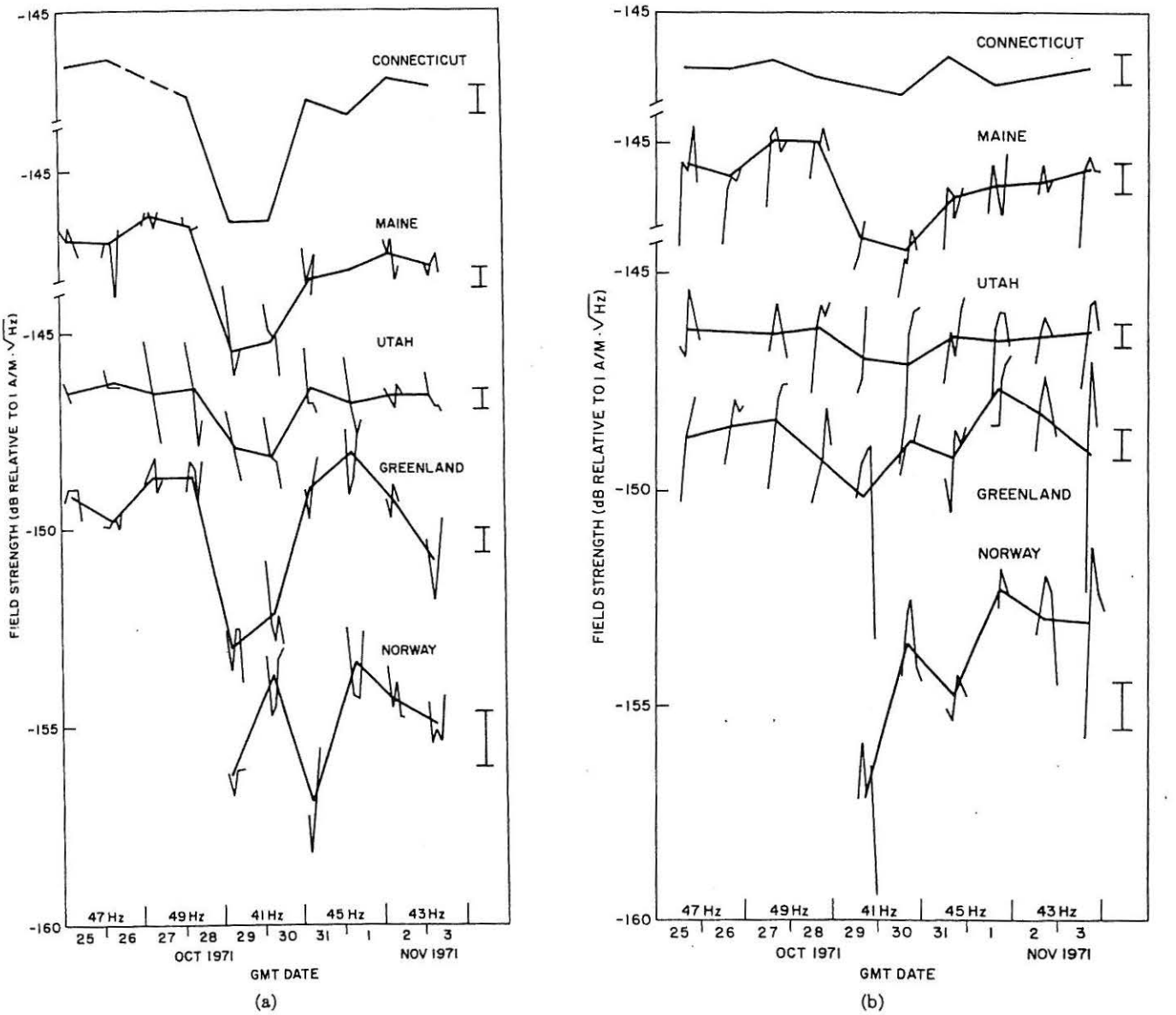


Fig. 5. (a) Nighttime propagation data in the 40-Hz band for October 25–November 3, 1971. (b) Daytime propagation data in the 40-Hz band for October 25–November 3, 1971.

path lengths of concern (2000 to 6000 km in the present case), such effects should be quite small on the scale indicated and should be infinitesimal in the case of nighttime data.

Geophysical effects, once again, are evident. A moderate magnetic storm commenced October 28, 1971 at 0800 GMT and lasted until October 30. Although no proton event occurred, a Forbush decrease was evident during this period as well, confirming that solar activity was pronounced. The geomagnetic index A_p reached a value of 27 during this storm, and a maximum change in the horizontal magnetic field strength at College, Alaska, of 920 γ was observed.

4) *May* 1972: A fourth example of Class I behavior occurred in May 1972. Fig. 6 contains data in the 41–49-Hz band recorded in Norway, Greece, and Saipan between May 15 and 19, 1972. Data were taken 24 h a day during this period, and the conditions of path illumination are so mixed that a separation of daytime from nighttime data has not been attempted. In Norway, for example, the receiver was never in darkness, and the Saipan and Greece paths were virtually never simultaneously in darkness. Data are arranged as in Fig. 5, with 24-h mean signal levels connected across the plot. In this case, however, the sample-by-sample data are equally indicative. The bounded vertical line segments to the right of the plot indicate the 80-percent confidence intervals both for individual samples (the outer brackets) and for 24-h mean values. Between May 15 and 16 all paths underwent a level decrease of 2.2 to 4.3 dB. The onset was most pronounced in Norway and Saipan at about 0600 GMT on May 16, followed by a second simultaneous drop in Greece and Saipan at about 1700 GMT that date. No data were acquired in Norway and Greece the following day, but recovery at these two sites seemed to be delayed until May 18 and 19. The Saipan data during this recovery

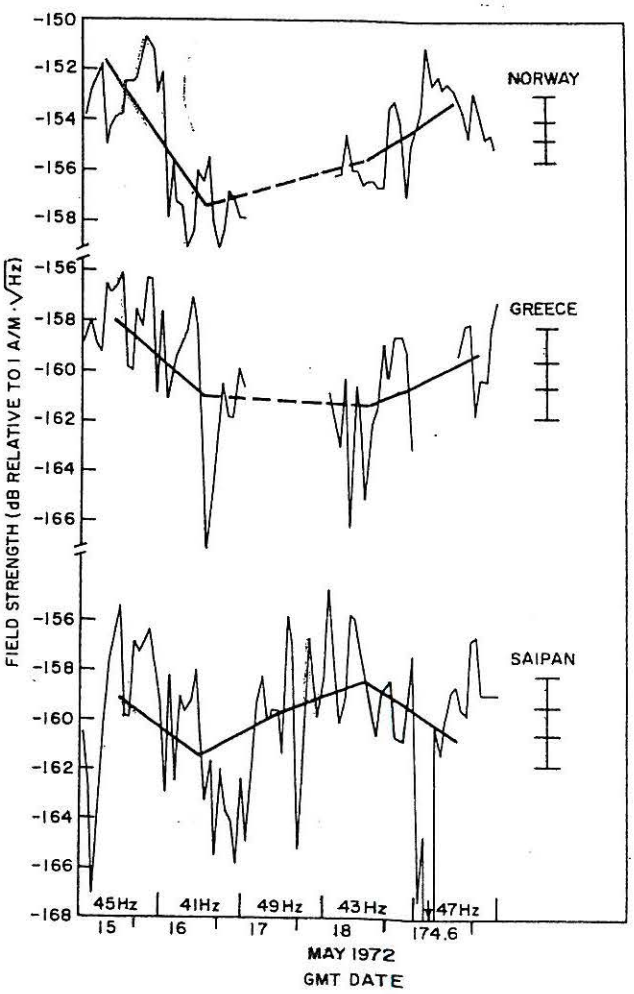


Fig. 6. Propagation data in the 40-Hz band for May 15–19, 1972.

period are less consistent and are complicated by a severe decrease at about 1000 GMT on May 19 which is less evident in data from the other two sites. Despite this confusing circumstance, there is an unmistakable trend both in the individual samples and daily means from May 15 through 19, showing a significant decrease (5 times the 80-percent confidence interval in Norway) and subsequent recovery.

Geophysical data for this period indicate that a magnetic storm commenced suddenly at 1849 GMT on May 15, reached a maximum A_p of 38, and had a maximum excursion in the horizontal magnetic field strength at College, Alaska, of 900 γ. A very pronounced Forbush decrease also occurred, reaching a maximum of 7 percent on May 16.

5) *October–November* 1972: A fifth example of Class I behavior (not indicated on Fig. 4) occurred in late October and early November of 1972. The available ELF signal data are nighttime 75-Hz transmissions recorded in Connecticut from October 31 to November 4, 1972. These data showed a pronounced rise from the normal mean signal level of −147.2 dBH at 0300 GMT to −145.2 dBH at 0400 GMT, followed by an equally pronounced continuous decrease to −149.4 dBH at 0730 GMT on October 31, 1972. This low level was maintained the following night, with recovery to around −148 dBH by 0730 GMT, and showed full recovery to the −147-dBH vicinity by the night of November 2, 1972. Once again, the change in mean signal level from night to night exceeded by far the 80-percent confidence interval of less than 1 dB.

A geophysical disturbance commenced October 30, 1972, with a PCA onset at Thule, Greenland, at 1400 GMT. A Forbush decrease began on October 31 and peaked at about 2000 GMT. A magnetic storm commenced at 1700 GMT on that date, reached a peak A_p value of 29, and reached a peak horizontal magnetic field deflection at College, Alaska, of 2170 γ.

The magnitudes of these magnetic storms are important because indications of anomalous behavior in the ELF signal were observed on every occasion during the two-years observation discussed here when a magnetic storm of comparable or greater magnitude than the one just considered occurred during measurements. The consequences of this circumstance are significant. The daily average A_p index published in the U. S. Department of Commerce's *Solar-Geophysical Data* indicates, for example, that an A_p value of 27 (corresponding to the October 1971 example) was exceeded in 28 of the 56 magnetic storms during the year 1971, a rather quiet year, and the mean duration of these storms was 2.5 days. If it could be assumed that the aforementioned five examples of ELF anomalous signal behavior are typical of such conditions, then it could be expected that a similar degree of disturbance might occur on 70 nights each year, or nearly 20 percent of the time (the daytime effects are not so pronounced). Further examples are presented in the following paragraphs which indicate that solar disturbance effects on ELF propagation are not as consistent as these five examples suggest.

6) *Examples of Lesser Significance*: The Class II examples in November 1970, March 1971, and October 1971 are no less interesting, but less concrete in their implications. Data acquired at the New England sites in the November 23–25, 1970 period display similar behavior. The nighttime 45-Hz signal measured in Connecticut declined by 2.6 dB on November 24 from its normal value of −155.4 dBH and recovered the following night. Massachusetts data declined about 5 dB from their normal value of −154.6 dBH on the same night and showed similar subsequent recovery. Daytime data displayed similar less prounced behavior (as in the fall 1971 example previously discussed).

Geophysical data for this case are less rewarding. The ionosphere was recovering from the effects of a solar eruption that occurred November 15–18 and led to the usual Forbush decrease, cosmic noise absorption increase, and moderate magnetic storm (peak A_p = 30 on November 21). However, the most prominent ionospheric effects of this disturbance were over by November 24, with only a moderate degree of excess cosmic noise absorption remaining.

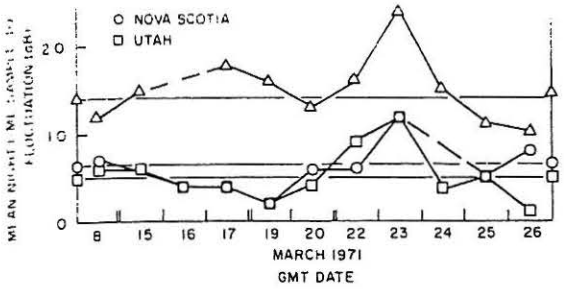


Fig. 7. Sample-to-sample fluctuation data in the 40-Hz band for March 8–26, 1971.

Between March 22 and 24, 1971 a second ELF propagation disturbance occurred which is difficult to explain as the result of solar influence. Nighttime data in the 40-Hz band from Connecticut, Utah, Nova Scotia, and Hawaii all displayed a much higher than normal degree of sample-to-sample variability during this period. Fig. 7 contains plots of the nightly mean sample-to-sample fluctuation observed at three of the sites during 11 nights of March 1971. The normal mean values are as indicated by the horizontal lines for each site. Data from Utah and Nova Scotia were very similar throughout the period and showed a pronounced peak on March 23, as did the data from Hawaii. The latter site experienced a mean sample-to-sample fluctuation of 2.4 dB on that date compared with its normal 1.4 dB. While these data are by no means overwhelming, they certainly are corroborative of each other and indicate a type of disturbance which has been observed from time to time.

There is no candidate geophysical explanation for this behavior; the sun was quiet during the entire latter half of March.

In the periods of October 13–14 and 17–18, 1971, data from Norway at 75 and 77 Hz displayed most unusual behavior. Between October 13 and 14 a drop in mean nighttime 75-Hz signal level of 3.6 dB occurred. Data acquired at 73 Hz on the following two nights were normal. Then, between October 17 and 18 a drop in mean nighttime 77-Hz signal level of 4.0 dB occurred. The 80 percent confidence interval for these mean data was about 0.7 dB. Data acquired simultaneously in Greenland and Utah showed no such abnormal behavior.

The ionosphere was in the final stages of recovery from a moderate magnetic storm that began on October 9, but there was no pronounced galactic cosmic ray disturbance or cosmic noise absorption between October 13 and 18.

The remaining example concerns unusual but slight *increases* in mean nighttime signal observed at Utah, Nova Scotia, and Hawaii on April 4, 1971 with 45-Hz transmissions. Also on this date each site recorded a single 1.4-h sample at 1100 GMT (0918 GMT at Nova Scotia, which was the last nighttime data point) that was the highest sample value received in the 41–49-Hz band during the entire month of measurements.

Once again there is an indication of possible solar influence. A moderate magnetic storm (peak A_p = 27; Alaska, of 1310 γ) commenced on April 3 and peaked the following date. No Forbush decrease took place and no pronounced cosmic noise absorption was observed.

C. General Observations and Discussion.

The examples of Class I and II behavior previously described indicate that solar phenomena have an influence on ELF propagation. The effects are most pronounced at night but can occur in the daytime as well. By far the most common effect seems to be a one- or two-day decrease in nighttime signal level of several decibels which is observed at sites in widespread locations both near to and remote from the transmitter. The examples of 1.6- to 7.1-dB night-to-night signal decreases observed at the relatively short-path New England sites are of interest for two reasons: 1) if they are short-path manifestations of a distributed ionospheric effect (i.e., an effect upon attenuation rate), then longer paths would be affected severely; 2) if they are manifestations of a local effect either at the transmitter or receiver (i.e., an effect upon modal excitation), then such local effects can be quite large.

The examples of similar behavior on longer paths do not clarify the issue. Fig. 5 indicates that paths to the north and northeast including but not restricted to those in the auroral zone (Connecticut, Maine, Greenland) and paths to the west (Utah), while approximately equal in length, are not affected equally. The exaggerated effect at the former sites suggests that northerly latitudes are affected to a greater degree than temperate latitudes, but the failure of the Norway data to obey the same trend suggests that even the former area is subjected to a varied influence. Such local phenomena as nighttime sporadic E, a common companion of solar activity, must certainly be considered as a candidate explanation in investigating these matters. The tendency for sample-to-sample variability to show agreement among the two auroral zone paths in Fig. 5 suggests that there may be strong short-term influences that affect the common subauroral segment of their path.

The data in Fig. 6 suggest that under some conditions, paths that remain entirely within the temperate latitudes can be affected as severely as those which pass through the auroral region and polar cap. Perhaps in these cases the local conditions at the transmitter should be suspected, and if they are responsible it is suggested that changes of mode excitation of 3 to 4 dB can take place from night to night.

The most promising result of this crude analysis is a seeming indication that solar influence upon ELF propagation is associated with the various indices of charged particle arrival in the vicinity of the earth. Decreases in galactic cosmic ray intensity and the onset of magnetic storms are most consistently associated with the observed ELF propagation anomalies. However, it should be noted that these solar phenomena do not always *degrade* the path or *lower* mode excitation efficiency. In

one example their result seems to have been to improve conditions slightly, and in another it seems to have led only to short-term variability in path conditions (this latter condition is, of course, somewhat degrading to communications, but may be less serious than a one- or two-day degradation of several decibels).

Finally, it must be noted that the degree of seriousness of these effects should not be overestimated. In no case does the evidence indicate that net degradation exceeds a few to several decibels. However, all of these results have relied on data that were integrated over tens of minutes to hours. Having established that even with this limitation there is evidence of significant solar/geophysical influence on ELF propagation, one should begin to ask whether shorter term influences also exist, and whether these influences might have an important effect on higher data rate transmissions. It should be evident that propagation research efforts continue to be necessary and will benefit from a transmitter of increased radiating capacity.

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Results of the Wisconsin Test Facility Buried Versus Elevated North–South Antennas Test

PETER R. BANNISTER, MEMBER, IEEE, FREDERICK J. WILLIAMS, J. ROBERT KATAN, MEMBER, IEEE, AND JOHN R. BALL

Abstract—In March and April 1973, the 76-Hz magnetic field strength, produced by the Wisconsin Test Facility elevated and (newly installed) buried north–south antennas, was measured in Wisconsin and Texas. The principal result obtained is that there is no measurable difference in performance between the two antennas.

INTRODUCTION

DURING the summer and autumn of 1968, H/I conductivity measurements (with 2-km antennas as the source) were made [1] along the rights-of-way for the north–south (NS) and east–west (EW) lines of the proposed Wisconsin Test Facility (WTF). The purpose of those measurements was to obtain an estimate of the effective conductivity under each of the lines. In the H/I induction method, a long insulated wire grounded at both ends is energized by an ac generator at the frequency of interest. The magnitudes of the magnetic fields are then measured at various distances and angles from the wire [2].

During August 1972 the effective earth conductivity (σ_e) beneath the NS and EW elevated antennas at 45 and 75 Hz was measured [3]. The H/I method was used with the two antennas alternately employed as the source. These measurements were performed mainly at distances of 45 and 75 km from the WTF transmitter, in line with and broadside to each elevated antenna. To be certain that the receiving sites were acceptable, 14 components of the received magnetic field were measured at each of the 50 sites and then plotted on a normalized cosine curve. The principal result obtained from these measurements is that the effective conductivity under the EW antenna (σ_{eEW}) is greater than that under the NS antenna (σ_{eNS}).

A comparison of these latest measurements [3] with the 2-km H/I estimates [1] for the WTF rights-of-way shows that the σ_e estimates were accurate to within a factor of 1.5 (except for the EW right-of-way estimates, which were off by factors of 2.6 at 45 Hz and 1.9 at 78 Hz).

During the last week in March and the first week in April 1973, in Wisconsin and Texas, the 76-Hz magnetic field strengths produced by the elevated and (newly installed) buried NS antennas were measured. The objectives of these measurements were 1) to compare the field strengths of the buried and elevated NS antennas, 2) to ascertain the repeatability of the August 1972 WTF effective earth conductivity measurements, and 3) to determine the reasons for the discrepancies between the summer 1968 and August 1972 values.

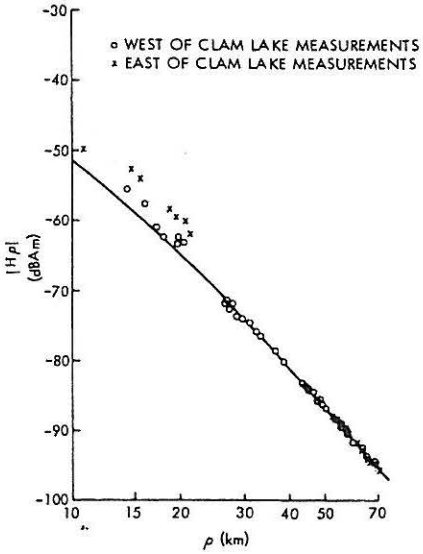


Fig. 1. $|H_\rho|$ versus ρ, 76-Hz elevated NS antenna, $\sigma_{eNS} = 2.2 \times 10^{-4}$ mho/m, $\delta_{eNS} = 3.9$ km, $I = 300$ A, $\phi = 90°$.

WISCONSIN RESULTS

During the March–April 1973 test, measurements were performed at distances ρ of 10 to 70 km from the WTF transmitter, approximately broadside to the NS antennas. To be certain that the sites were acceptable, 14 components of the received magnetic field were measured at each of the 60 sites and then plotted on a normalized cosine curve. A plot of the H_ρ component (in decibels per ampereturn per meter)[1] versus range for the WTF elevated NS antenna is shown in Fig. 1. These H_ρ values were normalized to a transmitter current I of 300 A and azimuth angle ϕ of 90° (i.e., directly broadside to the WTF NS antenna s). The solid line in Fig. 1 was derived [3], [4] by assuming a σ_{eNS} value of 2.2×10^{-4} mho/m; this is the value of σ_{eNS} measured during the August 1972 σ_e test [3]. From the figure, it can be seen that the theoretical and experimental values of H_ρ are in excellent

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[1] 1 dBAm is 1 dB referred to 1 At/m.

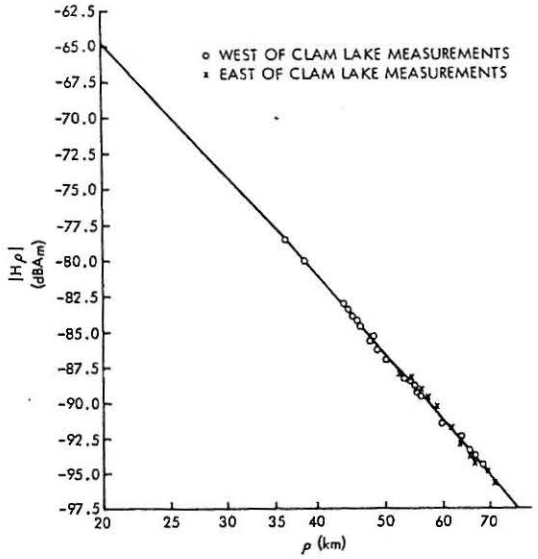


Fig. 2. $|H_\rho|$ versus ρ, 76-Hz buried NS antenna, $\sigma_{eNB} = 2.2 \times 10^{-4}$ mho/m, $\delta_{eNB} = 3.9$ km, $I = 300$ A, $\phi = 90°$.

agreement for measurement distances greater than 26 km. Thus, the repeatability of the August 1972 measurements is excellent.

It has been shown [5] that for the homogeneous isotropic earth case, the measurement distance must be greater than 7 earth skin depths ($\delta \sim 505/(f\sigma)^{1/2}$ m, where f is the frequency in hertz and σ is the uniform earth conductivity) for the H_ρ component to be inversely proportional to $\sigma^{1/2}$. Since 26 km is approximately 7 effective earth skin depths [$\delta_e \sim 505/(f\sigma_e)^{1/2}$ m] at 76 Hz, it appears from the agreement of experimental and theoretical H_ρ results that $7\delta_e$ is also a valid distance criterion for the geoelectrically complex WTF area.

The H/I (2-km) measurements were made at ranges of approximately 20 km. Referring to Fig. 1, we see that the Naval Underwater Systems Center (NUSC) 10- to 20-km measurements are grossly different east and west of the NS antenna. Thus, it appears that when the measurement distance is less than 7 effective earth skin depths from the source, the σ_e results will be in error. It has been shown recently [6] that for certain two-layered earth conditions, even the $7\delta_e$ measurement distance is too short for determining σ_e.

A plot of the H_ρ component versus range for the buried NS antenna at 76 Hz is shown in Fig. 2. The H_ρ values are normalized to $I = 300$ A and $\phi = 90°$. These measurements were taken at distances of 36 to 71 km from the WTF transmitter, approximately broadside to the buried NS antenna, and were repeated at each of the 35 sites. From this figure, it can be seen that the theoretical and experimental values are in excellent agreement. Thus, to within the experimental accuracy of the measurements (±0.1 dB), there is no difference in produced field strength between the buried and elevated NS antennas. There is also no difference in the radiation pattern of the two antennas—within the experimental accuracy of these measurements (±1°).

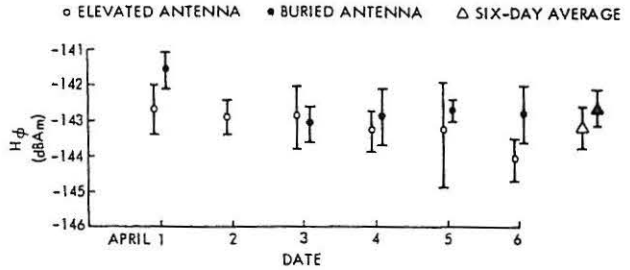


Fig. 3. 76-Hz elevated versus buried NS antenna field strengths received at Kingsland, Tex. (All data normalized to $I = 300$ A.)

TEXAS MEASUREMENTS

From mid-March through early April 1973, NUSC performed a conductivity survey of the Llano Uplift area of Texas, using the wave impedance measurement technique with the elevated NS antenna as the transmission source. An additional task, the far-field comparison of the elevated and buried NS antennas, was performed during the first week in April in Kingsland, Tex. This far-field site ($\rho \sim 1.85$ Mm) is approximately in line (i.e., $\phi \sim 0°$) with the NS antennas. The measurement period was divided into two segments: 1030 to 1430 GMT and 1530 to 2330 GMT. At 1430 GMT each day, the transmitter was switched from the buried to the elevated antenna or vice versa; however, the first two hours (1030 to 1230 GMT) were not used for the buried versus elevated comparison since this period coincided with the Texas sunrise.

The measured daily averages for the H_ϕ magnetic field strength component are presented in Fig. 3. It should be noted that some of the atmospheric noise estimates taken during this period were upper bounds to the noise; i.e., these noise estimates are suspected to be contaminated with 60-Hz local fields. Therefore, some of the 80-percent confidence intervals computed for each of the daily averages may be too large.

Receiver integration times of 30 min per sample were employed for the majority of these measurements, resulting in 36 samples for the buried antenna and 34 for the elevated antenna. Referring to Fig. 3, we see that the 6-day H_ϕ averages are -142.6 ± 0.5 dBAm for the buried antenna and -143.2 ± 0.6 dBAm for the elevated antenna. Since these confidence intervals overlap, there is no significant difference in the magnetic field strengths produced by the buried and elevated antennas.

CONCLUSION

The principal results obtained from these different range measurements are the following.

1) There is no difference in performance between the WTF buried and elevated NS antennas (within the experimental accuracy of the measurements).

2) The August 1972 WTF effective earth conductivity measurements are repeatable.

3) The summer 1968 H/I WTF area measurements are probably erroneous because the measurement distance was too short.

It should be noted that results obtained by M.I.T. Lincoln Laboratory personnel in Norway during the same time period also indicate that there is no measurable difference in performance between the buried and elevated NS antennas [7].

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Peter R. Bannister (M'69), for a photograph and biography, see this issue, page 418.

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Historical Background and Introduction to the Special Issue on Extremely Low Frequency (ELF) Communications

JAMES R. WAIT, *Guest Editor*

WITH the current trend to exploit more and more the upper reaches of the radio frequency spectrum, it is interesting to see renewed and vigorous activity at the bottom end. There are many reasons why we should reexamine the usefulness of electromagnetic waves in the range "just above dc." Foremost is the fact that the penetration of energy into conducting media is improved as the frequency is lowered. Also because of the extremely long wavelength (e.g. in free space $\lambda = 3000$ km at $f = 100$ Hz), the conventional fine scale structure of the medium does not seriously distort the wavefronts nor attenuate the signals to any extent. On the other hand, certain properties of the medium that are invisible to higher frequencies play a role in the determination of the propagation characteristics.

From an historical standpoint, it is significant that the genius Nikola Tesla [1] envisaged a world wide communication system using a huge spark gap transmitter located in Colorado Springs in 1899. A few years later he built a large facility in Long Island that he hoped would transmit signals to the Cornish coast of England. In addition, he proposed to use a modified version of the system to distribute power to all points of the globe. Unfortunately, his sponsor, J. Pierpont Morgan, terminated his support at about this time. A factor here was Marconi's successful demonstration in 1901 of transatlantic signal transmission using much simpler and far cheaper instrumentation. Nevertheless, many of Tesla's early experiments have an intriguing similarity with later developments in ELF communications.

Tesla proposed that the earth itself could be set into a resonant mode at frequencies of the order of 10 Hz. He suggested that energy was reflected at the antipode of his Colorado Springs transmitter in such a manner that standing waves were set up. The following quotation [2] is revealing.

> Recognizing in the existence of these waves, an unmistakable evidence that the disturbances had been conducting from their origin to the most remote regions of the globe and had been thence reflected, I conceived the idea of producing such waves in the earth by artificial means with the object of utilizing them for many useful purposes for which they might be found applicable.... I finally succeeded in reaching electrical movements or rates of delivery of electrical energy not only approximating but, as shown in many comparative tests and measurements, actually surpassing those of lightning discharges, and by means of this apparatus I have found it possible to reproduce whenever desired phenomena in the earth the same as or similar to those due to such discharges. For example, by the use of such a generator of stationary waves and receiving apparatus properly placed and adjusted in any other locality, however remote, it is practicable to transmit intelligible signals or to control or actuate at will any one or all of such apparatus for many other important and valuable purposes, as for indicating wherever desired the correct time of an observatory or for ascertaining the relative position of a body or distance of the same with reference to a given point or for determining the course of a moving object, such as a vessel at sea, the distance traversed by the same or its speed, or for producing many other useful effects at a distance dependent on the intensity, wavelength, direction or velocity of movement, or other features or property of disturbances of this character.

Since the era of Tesla, electromagnetic waves in the region of 60 Hz have been predominantly exploited for distribution of power via overhead conductors and buried cables. In fact, Tesla's invention of the ac polyphase technique was the forerunner of many of the systems that now continue to be the principal means of distributing electric power.

The possibility that electromagnetic waves in the 100 Hz range could be generated and transmitted without wires to useful distances was demonstrated probably for the first time by Conrad and Marcel Schlumberger in France before 1920 [3]. These pioneering applied geophysicists were primarily interested in using such electromagnetic (em) waves for prospecting for natural resources such as mineral deposits. The significant point about these early developments was that the earth was being excited electromagnetically in one region and the response was observed at a distance point (typically in the range from 100 m to 10 km). Many developments in electrical prospecting that used ac electromagnetic fields have been made over the past 50 years and I will not attempt to describe this history and recent developments. Interested readers are referred to a relatively recent edited textbook [4] on the subject that has been written for an electrical engineering audience.

Another related series of developments involves the propagation of natural ELF signals to great distances over the surfaces of the globe. The large amount of ELF energy in lightning discharges are here utilized as a source to

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excite the earth–ionosphere waveguide. Such signals have been observed to propagate with exceptionally low attenuation (e.g., 1 or 2 dB per 1000 km). A clear and concise account of these developments is given in the summary paper by D. Llanwyn Jones in this issue.

In the context of these early developments in ELF transmission techniques, it was only a matter of time before the artificial generation of sufficient power to excite the earth–ionosphere cavity or waveguide was successful. The basic concept is quite simple; one connects two or more grounded electrodes by an ac power source via insulated cables. Thus the source is really equivalent to a horizontal electric dipole at the air–ground interface. Because of the imperfect conductivity of the ground, vertically polarized signals are generated that couple into the waveguide formed by the earth's surface and the lower region of the ionosphere. Contrary to first impressions, the excitation or radiation pattern has maxima off the ends of the dipole with nulls in the broadside direction.

A realization of the concept that the earth–ionosphere waveguide can be excited artificially at ELF was demonstrated by the U.S. Navy and its contractors during the past ten years. The late Nicholas Cristofilos has been identified as an individual who played a central role in the early developments. Two papers (by J. Merrill and B. E. Keiser) in this special issue review some of the early history of this development that is now known as *Project Sanguine.*

The recent controversy surrounding Project Sanguine has now somewhat subsided. Many of the technical issues that were in contention are reviewed in a brief article by this writer [5] who can claim to have a measure of objectivity since he was not a Sanguine contractor. Also an open forum of the subject was held at a marathon session during the Ocean Engineering Conference held in Newport, R. I. in September 1972. Both the proceedings of the session and the edited transcript of the taped discussions are in the public domain [6], [7].

Following the Sanguine festival, this special issue was announced. All individuals who were known to have any interest in the subject were contacted. The National Academy of Sciences was invited to cosponsor this issue. They gracefully declined but not before pointing out that such a special issue was consistent with the recommendations of their ad hoc panel on Project Sanguine. Professor Henry G. Booker, Chairman of this panel, also encouraged me to proceed with this issue but he felt that his own involvement should be minimal. However, two other members of the N.A.S. panel, Prof. R. K. Moore and Dr. J. A. Mullen, agreed to serve on the editorial board. They were joined by D. D. Crombie and R. C. Kirby both of the Office of Telecommunications and Dr. R. Esposito formerly of the Raytheon Company. Prof. R. J. King of the Electrical Engineering Department, University of Wisconsin, Madison, served as deputy editor until his departure for Denmark just at the deadline for paper submissions on 15 September 1973. Later valuable assistance in the editing was received from W. E. Garner and Dr. J. R. Davis of the Naval Research Laboratory and Dr. Michael Burrows of the Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, Mass. A key role was played by Mrs. Dorothy Burdick who acted as secretary of the editorial board and handled the enormous amount of correspondence between the editor, members of the board, reviewers, and authors. Mrs. Burdick's activities were supported by the Environmental Research Laboratories of the National Oceanic and Atmospheric Administration. In this connection I would like to thank Dr. Wilmot N. Hess, Director of ERL/NOAA and Mr. Douglass D. Crombie, Director of the Institute of Telecommunication Sciences for their personal encouragement and support for my activity as guest editor. Also I should not fail to mention that my own secretary, Ms. Lana Slusher, has been extremely helpful in many supporting tasks to both Mrs. Burdick and myself.

Every paper, whether solicited or not, was examined by referees selected for their competence and objectivity. In some cases there were as many as six reviewers. Needless to say, I owe a great debt of gratitude to these individuals. They are listed alphabetically as follows: J. Adams, P. R. Bannister, W. Bensema, S. L. Bernstein, L. A. Berry, H. G. Booker, S. A. Bowhill, M. L. Burrows, C. Cabat, D. C. Chang, D. D. Crombie, D. Davidson, J. R. Davis, R. Esposito, J. E. Evans, E. C. Field, Jr., W. L. Flock, R. I. Gamow, W. E. Garner, A. S. Griffiths, D. A. Hill, H. G. Hughes, A. G. Jean, L. L. Jones, R. Kamper, R. J. King, R. C. Kirby, G. M. Lerfald, R. Linfield, S. W. Maley, M. McLintock, G. Miller, R. K. Moore, J. A. Mullen, M. Nesenbergs, C. W. Niessen, D. W. Novotny, R. A. Pappert, C. Polk, W. Reeder, H. E. Rowe, A. C. Scott, A. D. Spaulding, W. L. Taylor, W. F. Utlaut, L. B. Wetzel, E. C. Whipple, and D. P. White. At all times we received the greatest cooperation from Dr. D. L. Schilling, Editor-in-Chief of the IEEE Communications Society. We are particularly pleased that he has taken steps to minimize the inherent publication delays. Finally I should like to mention that the U.S. Navy has been most cooperative in releasing material for this issue. In particular, Dr. Bodo Kruger of the Navy's Project Sanguine Office, has been most helpful in seeing that we received submissions by the stated deadlines.

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Project Sanguine Interference Mitigation Research

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Abstract—The Navy's proposed extremely low frequency (ELF) communications system (Sanguine), which would use an earth-return circuit to excite the earth-ionosphere cavity, represents a potential electrical interference problem. The electromagnetic fields produced by Sanguine could influence other systems such as power distribution lines and telephone circuits, and other very long electrical conductors. This interference potential and the techniques useful in mitigating it are described. Also, data on power and telephone systems are presented that were useful in communications systems design tradeoff studies.

INTRODUCTION

INTERFERENCE mitigation research performed for Project Sanguine is described. This research was an element of a broad Environmental Compatibility Assurance Program, which is the research and development program for the assessment of the environmental impact associated with a Sanguine system. The objective of this program is to assure minimum adverse environmental impact during system construction and subsequent operations [1]. Research was directed to assess potential interference in electrical and electronic devices and other systems employing long conductors, and to develop techniques to mitigate or eliminate these potential interference effects. Included were theoretical studies of the expected electromagnetic environment in the vicinity of an antenna element and of the mutual coupling to systems employing long conductors. Laboratory studies of the susceptibility of devices to interference and of the effectiveness of devices to eliminate interference were also conducted. In addition, field studies to measure the electromagnetic fields near test facility antennas and the coupling into utility systems and fences, and demonstrations of the effectiveness of the interference mitigation techniques applied to model utilities located near a test facility were completed. A significant part of this research program was the construction of a test facility near Clam Lake, Wis., and the successful application of interference mitigation techniques to power and telephone systems serving that area. Finally, a series of parametric studies was conducted to determine the amount of interference mitigation that would have to be applied to power and telephone systems as a function of Sanguine system design parameters.

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ELECTROMAGNETIC FIELD CALCULATIONS

The principal components of a conceptual Sanguine transmitting system are the power amplifiers, the long insulated antenna cables, and the terminal grounds. Power amplifiers are connected to long buried insulated horizontal antenna cables and cause current to flow in the antennas. An antenna cable is terminated at each end in the buried bare conductors called terminal grounds. The resultant current flow sets up electric and magnetic fields in the vicinity of the antenna cable and its terminal grounds.

At points close to the antenna cable, the associated magnetic field is in phase with the antenna current, since the current flowing in the cable is the dominant contributor to the field. At points far removed from the antenna cable, the current flowing in the earth dominates the magnetic field.

The earth-return current causes a potential gradient (i.e., electric field) in the conductive earth, and this electric field is in phase with the earth currents. The electric field and the magnetic field are intimately related, and it can be said that the electric field is induced by the magnetic field. At points close to the antenna wire, the electric field leads the magnetic field and the antenna current by approximately 90°.

The electromagnetic field in the vicinity of the cable ends depends strongly on the design of the terminal grounds. Generally, the larger this system of buried bare conductors is made, the lower the current density flowing into the earth and the lower the resulting electric field. Therefore, to some extent, the field intensity in the vicinity of the cable ends may be limited by judicious terminal ground design. Furthermore, since the antenna cables would be long compared to the terminal grounds, the grounds influence only a small percentage of the total area.

The Sanguine concept requires that a number of long antenna cables be employed. These antennas would be arranged into a pair of orthogonal arrays of parallel elements spaced several miles apart. At a point in the system area, all antenna elements make contributions to the electromagnetic field. The exact nature of the field at such a point depends upon system characteristics,

uch as the relative phase of the antenna currents and the .etails of antenna layout.

The magnetic field at the earth's surface due to the ›uried antenna has two components which are described ›y [2]

$$B_z = -\frac{\mu_0 I}{2\pi}\frac{y}{d^2+y^2}; \quad B_y = \frac{\mu_0 I}{2\pi}\left[\frac{d}{d^2+y^2} - \tfrac{2}{3}\gamma\right],$$

$$\text{for } \gamma y < 0.2 \text{ and } \gamma d < 0.01 \quad (1)$$

where the assumed time factor is exp $(j\omega t)$ and the following are in MKS units:

- B_z vertical component of magnetic flux density;
- B_y horizontal component of magnetic flux density;
- I source current;
- f source frequency;
- ω $= 2\pi f$;
- μ_0 $4\pi \times 10^{-7}$;
- σ uniform earth conductivity;
- γ $= (j\omega\mu_0\sigma)^{1/2}$;
- y horizontal distance between line source and field point;
- d depth of burial source.

The mutual impedance between earth-return circuits has been a subject of interest to the telecommunications industry for more than 50 years. Researchers have investigated the mutual coupling between earth-return circuits and, thus, the surface electric field and earth-return current flow for a variety of situations [3]–[9]. Included are the cases of coupling between lines of infinite extent, between lines of finite extent with finite ground terminals, for lines on the surface and above the surface, and so on. The investigations include empirical studies that validate the theories and yield additional insight into the phenomena. While the electromagnetic field problem for the calculation of the electric fields produced by an insulated conductor buried in an inhomogeneous earth is quite complex, useful calculations can be made using the simplifying assumptions that the conductivity of the earth is uniform, and that conduction currents dominate displacement currents in the earth. Then it is necessary to determine empirically a value for effective conductivity that provides the best results in a given application.

The nature of the electric field near an extremely low frequency (ELF) earth-return circuit and remote from its ends can be described using the additional assumptions that the source circuit is straight, of great length, and buried near the surface of the earth. Then the electric field is given by Carson [3]

$$E_x = -\frac{j\omega\mu_0 I}{\pi(\gamma r)^2}[1 - \gamma r K_1(\gamma r)] \quad (2)$$

where $K_1(\gamma r)$ is the first-order Bessel function of the second kind, $r = (y^2 + d^2)^{1/2}$, and the other quantities are as defined for (1). A more complete discussion is presented elsewhere [10].

TABLE I
EARTH-SURFACE VALUES PRODUCED BY TWO NOMINAL CURRENTS

Frequency (Hz)	Electric Field Intensity (V/m)	Magnetic Flux Density (Wb/m²)
45	0.06	0.20×10^{-4} (0.20 G)
75	0.07	0.13×10^{-4} (0.13 G)

COMPARISON WITH COMMERCIAL POWER SYSTEMS

Given the tested effectiveness of interference mitigation devices for utility systems which could be affected by Sanguine, the Navy adopted for conceptual system studies an electric field intensity limit of 0.07 V/m for the horizontal component at the surface of the earth above a buried antenna. Therefore, for an antenna buried about 2 m deep in soil with an effective conductivity of 5×10^{-4} mho/m, antenna currents of 150-A nominal value at 45 Hz or 100-A nominal value at 75 Hz would be used as environmental guidelines for design studies. Table I shows the earth-surface values directly above the antenna that would be produced by the preceding nominal currents [1].

Since it was necessary during interference mitigation studies conducted at the Wisconsin Test Facility to measure the electric and magnetic fields produced by the experimental antennas, it was opportune to measure existing 60-Hz fields as well.

A total of about 400 sets of electric field data were collected from 1967 through 1971, during the various Sanguine environmental studies. Two hundred data points were selected that were not associated with some given power line or other source of earth current. An analysis of these data yielded the following results [1]:

maximum electric field value: 0.040 V/m
mean electric field value: 0.003 V/m.

Another 171 data points from the 60-Hz data base could be identified with power systems which could be regarded as sources of earth currents. These data were collected at consumer locations serviced by power distribution companies. As measured, it is the electric field that exists between the home and the garage, for example, or between adjacent homes. An analysis of the 171 data points collected near consumers' homes yielded the following results:

maximum electric field value: 0.525 V/m
mean electric field value: 0.094 V/m.

The data show that existing 60-Hz electric fields on consumers' properties are the same order of magnitude as the field expected directly above a Sanguine antenna, and values an order of magnitude higher can be observed.

The electric fields generated by various small appliances also were measured. Some typical values 30 cm from the appliances are shown in Table II.

TABLE II
ELECTRIC FIELD INTENSITIES GENERATED BY VARIOUS SMALL APPLIANCES

Small Appliance	Electric Field Intensity (V/m)
Electric blanket	250
Broiler	130
Phonograph	90
Iron	60
Food mixer	50
Hair dryer	40
Television	30
Vacuum cleaner	16
Electric range	4

TABLE III
RECOMMENDED INTERFERENCE THRESHOLDS

Minimum Difference Frequency[a] (Hz)	Recommended Threshold[b] (V)
Flicker	
8	0.02
15	0.2
25	0.7
Neutral to remote ground	6

[a] Minimum difference frequency is the difference between 60 Hz and the Sanguine frequency.
[b] On 120-V home circuit.

Finally, it should be noted that it is not unusual to encounter electric fields of 5000 V/m or greater under modern high-voltage transmission lines.

A large number of 60-Hz magnetic field measurements also have been made at many locations to characterize the existing electromagnetic environment [1]. It has been found that 60-Hz magnetic flux densities vary over a wide range even over relatively small areas. For example, the magnetic field in a modern office building varies in magnitude from several gauss (1 G = 10^{-4} Wb/m^2) near electrical equipment to several milligauss in the middle of a large room. Magnetic fields in homes also were observed to vary widely in intensity. Some consumer products generate fields as intense as tens of gauss in their vicinity.

In succeeding sections, the susceptibility of systems employing long conductors and of electrical and electronic devices to the fields expected in the vicinity of a Sanguine system will be described, as well as techniques that have been employed successfully to eliminate potential interference effects.

RESEARCH SUMMARY

The theoretical portions of the interference mitigation research [12] dealt with the calculation of field strength and induced voltage. The experimental studies involved both laboratory and field tests to determine susceptibility and effectiveness of appropriate mitigative measures. The field tests were conducted at the site within the Chequamegon National Forest in North Central Wisconsin. This Navy Test Facility, located near Clam Lake, Wis., consists of two orthogonal 14-mi (22-km) antennas, (forming a cross) with the transmitters located at the intersection. Each antenna wire is supported on ordinary utility poles and is terminated at each end in a low resistance distributed ground spread over a distance of about 2 mi.

For test purposes, the antennas were operated with currents up to 300 A singly or simultaneously, with any phase relationship between 0° and ±180°.

The following are summaries of the principal areas of research regarding the influence of Sanguine fields on metallic conductors.

Power Systems

Power systems engineers are acquainted with the problem of inductive interference in telephone, telegraph, or railroad communications systems due to the flow of zero-sequence current in a power system that results from phase unbalance or unequal phase loading. The operation of an ELF earth-return antenna can produce interference effects on single-phase power distribution lines through a similar coupling mode. Thus, voltages proportional to the current in the ELF antenna will appear in the power system as interference.

These interference voltages can be separated into two types. The first, which appears between the line and neutral conductors of the power system, is responsible for two different effects. One of these is the flicker produced in both incandescent and fluorescent lights. The other is flicker that appears in the vertical size of a television picture, due to the effect of the interference voltage on the vertical drive circuit of these sets. The second type of interference is the accumulation of voltage on the neutral of the power system with respect to remote ground. This voltage must be controlled to permit continued safe operation of the power system.

The flicker voltage threshold is determined by the maximum tolerable interference voltage on the home circuit. A conservative flicker perception threshold as a function of difference frequency is recommended in Table III. This criterion is based on the minimum difference frequency sensitivity observed on a variety of electrically powered consumer and commercial products [12], [13]. For example, the 200-mV level assumes that the interference frequency is only 15-Hz different from the commercial power frequency, that the consumer uses the most sensitive type of product in his home or factory, and that the consumer is particularly sensitive to light flicker. This threshold for the home (or factory) circuit must be referred to the primary side of the distribution transformer to determine the maximum allowable induced transverse voltage. In the example, 200 mV would be the result of 12 V of transverse interference on 7.2-kV systems, with even greater levels of transverse interference on the primary side allowable for power systems that operate at higher distribution voltages.

The maximum tolerable interference voltage between the grounded neutral wire and a remote ground is determined by the perception current threshold and safety considerations [14]. It is recommended that the threshold for this interference effect be 6 V to ground.

Since the flicker voltage does not appear across phase-to-phase connected transformers, this interference can be eliminated by converting the distribution system to phase-to-phase connected distribution transformers. The neutral-to-ground voltage can be eliminated by isolating the primary and secondary neutrals. A more complete discussion is given elsewhere [15], [16].

Finally, the potential for effects on system protection has been investigated with the conclusion that protective relays would continue to operate normally in the presence of the induced voltages that could be expected [17].

Telephone Systems

Since telephone lines are normally terminated to ground at the telephone central office, the electric field produced by a Sanguine antenna causes an interfering voltage-to-ground to appear on the telephone plant. The magnitude of the induced voltage depends on the details of the path from the central office that the telephone line follows with respect to the antenna. To permit safe operation of the telephone system exposed to a Sanguine environment, the induced voltage-to-ground must be limited to 50 V ac rms or less at every point in the telephone system from the central office to the customer's telephone. (This value is consistent with telephone industry proposals both in the United States and internationally.) This can be accomplished by the use of multiwinding neutralizing transformers. These transformers operate on the principle that one winding, called the primary, is connected to a wire that is grounded at both ends within the exposed telephone cable and that senses the longitudinal voltage. This causes a current to flow in the primary, which in turn introduces in the secondary windings a voltage that is connected in series with the telephone pairs and is 180° out of phase, thus counteracting the induced voltage [18].

Where the induced voltage is less than the 50-V safety criterion, operational problems may also be present. Such is the case where telephone set ringers are connected to ground, a situation frequently encountered on party lines in rural areas. To prevent false bell ringing due to Sanguine interference, additional mitigation in the form of ringer isolation devices must be installed [19].

The mitigation techniques described herein were applied to a commercial telephone plant exposed to Sanguine interference in the vicinity of the Wisconsin Test Facility. These measures were proved effective, as evidenced by the virtually interference-free performance of this plant over a period of more than 5 years [20], [21].

Pipeline Systems

Electromagnetic coupling theory adequately describes ELF coupling to pipelines so that induced voltages and currents on pipes can be predicted in a Sanguine-generated environment. The theories have been validated by field measurements.

Pipeline research and development permit the following conclusions.

1) Induced voltages and currents are directly proportional to the antenna current and vary with the angle between the pipeline and the antenna.

2) Induced pipe-to-soil potentials are generally inversely proportional to pipeline diameter (larger diameter increases the exposed area, while the greater wall thickness and increased circumference reduce the unit length longitudinal impedance).

3) Pipeline longitudinal currents are proportional to pipeline diameter.

4) Induced voltages increase by a small amount as pipeline coating quality is increased (a 2:1 increase for a 15:1 increase in coating quality).

Corrosion rates for alternating currents have been determined relative to rates without alternating currents. The ac corrosion rates are approximately 3 percent of those observed for direct currents. An increase in soil resistivity of 50:1 reduces corrosion rates by 50 to 80 percent.

The present extensive use of insulating joints and cathodic protection devices near ordinary 60-Hz power lines provides a proven means for controlling corrosion attributable to a Sanguine system.

Railway Systems

Theories describing electromagnetic coupling at ELF can be used to predict maximum induced voltages and currents on rails and railroad signal and communications circuits [1].

Laboratory tests indicate that railway circuit components are not susceptible to low-level ELF interference. Interference voltage levels vary from 10 V to produce relay coil hum, to 15 V to produce contact chatter or follow-through. The relay is the most sensitive element in the circuit.

Predicted voltage levels based on coupling theories were compared with data measured on railway systems. The results showed that it is possible to predict coupling adequately for given situations. Measured data were within 4 dB of computed data on the average.

Measured interference on rails was low, as anticipated. The rails are continuously grounded through the ballast resistance of the roadbed; therefore, significant longitudinal voltage buildup does not occur. Transverse voltages do not appear across rails, as the track system behaves as a balanced electrical circuit.

Wire Fences

The impact of induced ELF voltages on fences has been analyzed, field tests have been performed to determine practical methods for reducing induced voltages, several

mitigation devices have been produced, and the likely extent of the impact of fence interference has been defined.

Induced voltages on wire fences can be avoided without reducing the intended utility of the fence. The physical continuity of the fence is maintained, while the electrical length of the fence is limited by the mitigation process. This is done by including high electrical impedance devices in the fence. The mitigation devices are made and installed so that the restraining influence of the fence is not reduced.

Electric fences do not require interference mitigation under ordinary circumstances. The electrical properties are desirable from the user's point of view when the charging unit is attached to the fence. Induced voltages on the fence are negligible under these circumstances.

The impact of an ELF antenna that operates at reasonable current levels on wire fences has been assessed. Two surveys were conducted in Wisconsin to determine typical fence characteristics. In the first survey, a county-wide sampling was made which showed that most fences were only several hundred feet long. The second survey was a census of all fences in a 515-mi^2 (1333-km^2) area near the test site. That survey showed that only about 20 percent of the area contained any type of fence, that the typical fence was about 1300 ft (396 m) in total length (4 sides), and that 90 percent of the fences were less than about 3000 ft (914 m) long. The data from the census were then used in theoretical studies. The results showed that only a small percentage of the total number of fences in a typical area might require some attention. Furthermore, that small percentage would have to be very close and parallel to an antenna.

Consumer Products

Electrically operated consumer products generally found in the home are designed and manufactured so that ordinary variations in commercial power distribution voltage and frequency have no effect on the products, or the effect occurs for such a brief period that the nuisance is only momentary.

The sensitivity of most consumer products to ELF interference has been determined in laboratory tests and has been demonstrated at the Wisconsin Test Facility. Devices such as clocks, radios, and high-fidelity recording equipment exhibit sensitivities in the order of 10–20 V. Lamps and television sets are most sensitive, exhibiting interference threshold levels of about 200–400 mV. These levels effectively establish the transverse voltage interference threshold for power distribution systems.

The voltage supplied by power distribution systems is not a constant value. The voltage changes as the consumption on the distribution line changes. The voltage is reduced by a small amount during periods of heavy consumer demand; for example, during periods of hot weather when air conditioning loading is heavy. The voltage may be slightly higher than the nominal value during evening hours when only small appliances such as lamps and television sets are operated. These changes in voltage are not troublesome because most appliances are designed to operate acceptably for long periods of time on either relatively high or low voltages. Generally, the voltage varies between 110–120 V, but during critical periods, the voltage might be between 105–125 V. These changes indicate that most consumer devices are not susceptible to long-term 60-Hz interference fluctuations of plus or minus 10 V.

Commercial Products

A wide variety of products, which could be classified as commercial products, were studied to determine their susceptibility to ELF interference. Operating experience in existing 60-Hz environments indicates that the interference potential of a conceptual Sanguine system on this generic class of equipments is low. The research studies, which consisted mainly of environmental surveys and simulated Sanguine electric and magnetic field-intensity measurements, confirmed that this is the case. The study also showed that effective ELF mitigation techniques, developed to suppress 60-Hz interference, are applicable in a Sanguine-generated environment, should mitigation be necessary in unusual situations.

The equipment classified as commercial products included communications systems, medical electronic devices, scientific measuring equipment, industrial control equipment and monitoring devices, and avionics equipment.

Cardiac Pacemakers

Interference from external electromagnetic fields on cardiac pacemaker function has been reported with virtually all types of pacemakers [22]–[27]. It has recently been recognized that interference can even be caused by naturally occurring potentials of voluntary muscle origin [28]. In 1970 a research program was initiated by the Navy to determine whether even the most sensitive cardiac pacemaker would be affected by the magnetic fields in the vicinity of a Sanguine antenna. This research included bench tests on a number of synchronous and asynchronous pacemakers to determine direct injection susceptibility levels and tests of the most sensitive synchronous pacemakers while implanted in test animals and exposed to magnetic fields of up to 30 G (3×10^{-3} Wb/m^2) at 60 Hz. It was found that synchronous pacemakers with unipolar electrodes, in which the return path for the sense/stimulus electrode is through body tissue, were most susceptible to magnetically induced voltages in the pacemaker leads. Based on the tests in animals and on the effective loop area of human implants, it was concluded that the minimum magnetic field that could produce interference with the most sensitive pacemaker with the largest unipolar electrode loop was about 1 G at 60 Hz. (It should be noted that interference is defined as any change in pacemaker rate. Modern synchronous and demand pacemakers are designed to revert to a fixed rate in the presence of ELF signals such as those induced by the aforementioned magnetic fields. Thus, the criterion for interference is quite conservative.) The maximum

magnetic field expected directly above a Sanguine antenna is 0.2 G (2×10^{-5} Wb/m^2) at 45 Hz and 0.13 G (1.3×10^{-5} Wb/m^2) at 75 Hz. Therefore, it was concluded that there was no potential for cardiac pacemaker interference due to magnetic fields near Sanguine antennas. This work is described in more detail elsewhere [29]. Since this work was concluded, Smyth *et al.* [30] conducted a clinical study using 53 patients with permanently implanted pacemakers in which the patients were exposed to 100-Hz magnetic fields of up to 1 G (10^{-4} W/m^2) rms in an active magnetometer. The results reported previously, based on the animal study, are in complete agreement with the clinical study.

Finally, the work of Parker *et al.* [27] provides additional insight and perspective on the potential for interference with cardiac pacemaker function. Based on his clinical studies of patients with implanted electrodes, the following conclusions can be drawn: implanted pacemakers with bipolar electrodes are approximately 50 times less susceptible than those employing unipolar electrodes; limb-to-limb potentials of 2–3 V using standard posted electrocardiographic electrodes are necessary to produce interference voltages on unipolar electrodes of sufficient magnitude to interfere with sensitive synchronous and demand pacemakers at 60 Hz. (The pacemaker would revert to its normal interference mode and would continue to operate.) Thus, there is evidence to believe that the electric fields directly above an antenna element (0.07 V/m) would also not interfere with cardiac pacemaker operation.

DESIGN TRADEOFF STUDIES

The impact of a Sanguine system on the power and telephone systems in a given area depends on the details of the Sanguine system design. Parametric studies of power and telephone interference mitigation were carried out to permit comparison of various conceptual designs of Sanguine systems for system optimization purposes.

Examples of these parametric studies are presented here by considering two rural power systems and two telephone systems. For the case of the power systems, the first system (system *A*) serves about 400 mi^2 (1035 km^2) and employs about 300 mi (483 km) of single-phase line. The second (system *B*) serves about 100 mi^2 (259 km^2) and has about 60 mi (96.5 km) of single-phase line. The antenna system was assumed to include East–West and North–South elements. The studies included the influence of such system parameters as antenna line spacing, antenna position, antenna current and frequency, total system area, effective earth conductivity, and interference thresholds. Two positions were studied: the first locates the grid so that the power system substation is centered in a grid square; the second has the substation on an antenna intersection. Sample results of the study are given in Table IV. When these results are averaged on a per-square-mile basis, they can be approximately described by the following rules for the amount of rebuilding necessary within the area of a Sanguine system:

TABLE IV
SUMMARY OF POWER SYSTEM INTERFERENCE MITIGATION STUDIES

Antenna Current (A)	Position 1 (mi)	Position 2 (mi)
System *A* (400/mi^2)		
25	208.5 (335 km)	257 (413 km)
50	281.2 (452 km)	298.7 (481 km)
100	293.3 (472 km)	300 (483 km)
System *B* (100/mi^2)		
25	24.2 (38.9 km)	24.7 (39.7 km)
50	35.7 (57.4 km)	56.9 (91.6 km)
100	45.3 (72.9 km)	58.2 (93.6 km)

Light flicker threshold: 200 mV on 120-V line.
$\sigma = 5 \times 10^{-4}$ mho/m.
$f = 75$ Hz.
Line spacing = 10 mi (16 km).
Position 1: Substation centered in grid square.
Position 2: Substation at antenna intersection.

number of miles of single-phase line to be rebuilt

$= 0.01(I)^{1/2}$ mi/mi^2 $(0.06(I)^{1/2}$ km/km$^2)$, spacing > 5 mi (8 km) and $I < 50$ A

$= 0.72$ mi/mi^2 (0.45 km/km^2), spacing < 5 mi (8 km) or $I > 50$ A.

The equation should not be applied for systems with much larger spacing (e.g., >15 mi or 24 km), since the interference effects will be overestimated. Note that for systems with antenna spacing less than 5 mi or with currents in excess of 50 A, all single-phase lines are rebuilt and further increases in the current require no additional rebuilding within the system area.

The estimation of power system interference mitigation in the area outside the antenna system is accomplished by locating certain electric field contours and noting that the rebuilding requirement decreases as the distance from the system increases. The electric field in the fringe area is calculated using the uniform earth theory. In calculating the width and area of the fringe for a given field level, the simplifying assumption is made that the contour representing the level is uniformly spaced from the system edges.

The required number of miles of rebuilding is obtained by applying the following figures to each of the particular fringe areas:

1) area between system and 9-V/mi (5.6-V/km) contour: 0.72 mi/mi^2 (0.45 km/km^2);

2) area between 9- and 4-V/mi (5.6- and 2.5-V/km) contour: 0.67 mi/mi^2 (0.42 km/km^2);

3) area between 4- and 2-V/mi (2.5- and 1.3-V/km) contour: 0.42 mi/mi^2 (0.26 km/km^2);

4) area between 2- and 1-V/mi (1.3- and 0.6-V/km) contour: 0.15 mi/mi^2 (0.09 km/km^2);

5) area between 1- and 0.5-V/mi (0.6- and 0.3-V/km) contour: 0.005 mi/mi^2 (0.003 km/km^2).

TABLE V
TELEPHONE EXCHANGE CHARACTERISTICS

Exchange	Customers	Miles of Line	Area Served
A	1287[a]	210 (338 km)	750 mi² (1940 km²)
B	198	200 (322 km)	550 mi² (1420 km²)

[a] 1125 customers are in one town.

TABLE VI
SUMMARY OF TELEPHONE INTERFERENCE MITIGATION STUDY FOR FRINGE AREA

Electric Field (V/mi)	Transformers per square mile
9 (5.6 V/km)	0.016 (0.0062 per square kilometer)
6 (3.7 V/km)	0.004 (0.0015 per square kilometer)

These numbers were obtained by studying the power systems immersed in a uniform field and calculating the required mitigation. The results, weighted by area, were then averaged to obtain the preceding data.

An example of the studies on the telephone plant within the area of a Sanguine antenna is presented in the following paragraphs for two telephone exchanges with the characteristics shown in Table V. The parameters used were the same as for the power system study. The results of this cost study are that the number N of required neutralizing transformers per square mile of Sanguine system area is given by

$$N = KI$$

where I is the antenna current in amperes and K depends upon the antenna cable spacing. For example, for a 5-mi (8-km) spacing, $K = 10^{-3}$ or 0.1 transformer per square mile (0.04 per square kilometer) for a 100-A system.

A parametric study was performed to determine the telephone system interference mitigation in the area outside the antenna system. The same two telephone systems used to determine the mitigation cost in the system area were used in the fringe area mitigation study. This study assumed that the telephone system areas were immersed in a uniform electric field of 6 and 9 V/mi (3.7 and 5.6 V/km). The results are shown in Table VI. Note that the number of transformers required is reduced by a factor of 4 as the E-field level is reduced from 9 to 6 V/mi (5.6 to 3.7 V/km).

CONCLUSION

The Interference Mitigation Research Program has been successful in identifying potential interference to metallic conductors, developing a theoretical basis for understanding and predicting interference levels, and has verified experimentally both the need for and the effectiveness of appropriate mitigation methods. Many of the mitigative measures employed are similar to techniques previously used to protect communications facilities and other wire lines from the adverse effects of induction from commercial power systems under fault or other abnormal operating conditions.

Insight into Sanguine system design parameters and their effect on the extent and nature of the mitigative measures has been gained, and algorithms have been generated which will be useful in design tradeoff studies.

Successful operation of commercial power telephone systems exposed to the influence of the antenna signal at the Wisconsin Test Facility has demonstrated that compatible operation of wire facilities in a Sanguine environment is possible. For the antenna current levels used at the test facility, the mitigation requirements were such that operational limitation of the modified utilities was minimal.

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The Sanguine Biological-Ecological Research Program

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Abstract—An overview of laboratory and field studies, completed and in progress, which are designed to disclose possible effects on organisms of a Sanguine system, is presented. The extremely low frequency (ELF) electric and magnetic field levels associated with a Sanguine system are about 0.07 V/m and 0.2 G, respectively, at the surface of the earth directly above a buried Sanguine antenna. The Sanguine Division of the Naval Electronic Systems Command initiated research in 1969 to determine whether biological or ecological effects could be expected from exposure to these low levels. The research spans a broad spectrum of biological sciences, from enzymes to mammalian behavior, and from bacteria and slime molds to primates. Results of completed studies are summarized, and those studies still in progress are discussed. Research results to date show no indication that exposure to ELF field levels associated with a Sanguine system would have any effect on biological or ecological systems. Results of research in progress will be reviewed when available to determine future directions of the program.

INTRODUCTION

THE Sanguine biological–ecological research program had its beginning in 1967. Since it was known that uncontrolled microwave radiations have biological impact, it was advisable to consider whether extremely low frequency (ELF) radiation would have adverse effects on biota. The Sanguine Division of the Naval Electronic Systems Command performed a search of the scientific literature in 1967. This literature search produced information on biological effects of microwave radiation, ionizing radiation, dc magnetic fields, and electrostatic fields. Very few experiments on biological effects of ELF radiation were reported. Since this research provided no basis to judge whether ELF radiation would produce biological effects, it became necessary to formulate a biological research program.

In the formulation of any research program, generally, there are well-established cause-and-effect relationships that provide a springboard for further investigations. Accumulated experience provides a foundation of methodology and theory on which further knowledge is built and the attainment of research goals facilitated. No such luxury was available in structuring an ELF biological research program. To compound the difficulties, the Sanguine biological program faces the possibility of having to prove a negative hypothesis, i.e., that there may be no demonstrable effects on living systems. We all know that negative proof may stretch to infinity, but it still leaves something to be desired in the minds of some.

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It is well known that microwave energy can produce adverse thermal effects in living tissues. But ELF radiation, even at levels many times higher than those expected from a Sanguine system, contains too little energy to produce measurable heating effects. Ionizing radiations, which are at higher energy levels than microwaves, can produce mutagenic effects. This makes the possibility of genetic effects due to ELF radiation much more remote than even thermal effects. Furthermore, there have been no biological effects reported from the 60-Hz electric and magnetic fields produced in today's environment by commercial electric power systems. These fields are similar in both frequency and energy levels to those a Sanguine system would produce.

There is evidence that electroreception leading to physiological and behavioral responses can occur in animals exposed to low energy fields at frequencies below conceptual Sanguine frequencies. Wever [1] reports that the diurnal rhythmicity of human body temperature is altered by exposure to low intensity (2.5-V/m peak voltage) 10-Hz electromagnetic fields, as well as to natural electromagnetic fields. Gavalas *et al.* [2] report a significantly faster response in monkeys exposed to low energy fields at 7 Hz but not at 10 Hz. Bullock [3] points out that passive reception of low frequency feeble voltage gradients has so far been demonstrated in sharks, eels, catfish, and electric eels, and that in sharks it is tuned to 0.1–10 Hz; above 10 Hz sensitivity falls off sharply.

The initial research funded by the Sanguine Division was a group of experiments performed by Hazleton Laboratories in 1969 (see [5]). These experiments were chosen to represent several biological areas that might indicate directions for further research. Other research, including both laboratory and field studies at Sanguine test facilities, was also initiated at this time. All of these investigations were progressively reviewed to determine future directions. It became clear, as these studies proceeded, that it would be desirable to open up additional areas of research. Therefore, nine investigations were initiated at various universities. These investigations span as much as nine studies can, the broad spectrum of biological sciences, from enzymes to mammalian behavior, and from bacteria and slime molds to primates. New field investigations were also initiated. Table I presents the total number of studies, and includes those completed and those still in progress.

Simulation of ELF Electromagnetic Fields

An ELF electromagnetic field is most easily simulated in the laboratory by generating the electric and magnetic

TABLE I
SANGUINE BIOLOGICAL–ECOLOGICAL STUDIES COMPLETED AND IN PROGRESS

Organism	Test System								
	Genetics	Fertility	Physiology	Growth and Development	Biochemistry	Biorhythms	Behavior	Orientation	Population Surveys
Plants									
Bacteria	x			x	x				x
Slime mold	x			x	x	x			
Bean	x		x	xx					
Buckwheat				x					
Corn				x					
Forest and herbaceous species									x
Onion	x								
Silk tree						x			
Sunflower				x					
Animals									
Sea anemone							x		
Snail							x		
Scallop							x		
Sea squirt							x		
Shrimp							x		
Crab							x		
Soil mites									x
Springtails									x
Flour beetle						x			
Fruit fly	x								
Blue gill							x		
Croaker							x		
Eel						x	x		
Pin fish							x		
Salmon						x	x		
Frog				x					
Salamander			x						
Painted turtle							x		
Birds (wild)									x
Chicken		x	x	x			x		
Duckling							x		
Gull chick								x	
Homing pigeon								x	
Mammals (wild)									x
Mouse						x			
Rat		x		x	x		x		
Dog			xx		x				
Monkey			x		x		x		
Man		x	xx		xx		xx		

field components separately. Since induced eddy currents in conductive media do not appreciably distort magnetic fields at the ELF of interest to Sanguine, typical Helmholtz coil configurations can be used to produce the magnetic field component. The test subject is then confined to a volume of space where the known generated magnetic field is of uniform strength.

The electric field near a buried Sanguine antenna exists in the earth as well as in the air above the surface of the earth. Parallel flat metallic plates can be used in the laboratory to generate the electric field in air. Generating the proper electric field in a conductive medium for a laboratory experiment depends on the subject under test [4]. In experiments on organisms in water or soil and in experiments with plants, flat parallel plates in contact with two opposite sides of the water or soil can be used to simulate the electric field in the conductive medium. This arrangement could be used to generate the field in a conductive medium in experiments with animals that walk on the soil if the moisture content of the soil could be controlled. However, in addition to the problem of urine changing the moisture of the soil in a laboratory simulator, the moisture content required to achieve the proper conductivity may provide suboptimal conditions for the subject under test. Suboptimal living conditions were apparent in the rat fertility study at Hazleton Laboratories in 1969–1970 [5d)]. It was difficult to rear the offspring on moist earth.

The important consideration in simulating the electric field in a conductive medium is the transfer of current to the animal from the conductive medium containing the electric field. Therefore, in subsequent laboratory experiments with animals, where appropriate, the floor was made of parallel metal rods connected together electrically by resistors, and each end bar was connected electrically to its respective parallel plate electrode by a resistor. The resistor values were chosen to simulate the source resistance that the test subject would experience

if he were walking on the ground in the vicinity of a buried Sanguine antenna.

The location of highest electromagnetic field intensity in a Sanguine system area would be near an antenna element. The electric and magnetic field levels on the surface of the earth directly above a buried antenna would be about 0.07 V/m and 0.2 G, respectively. At points close to the antenna, the electric and magnetic field components are approximately in time quadrature. Therefore, in Sanguine laboratory research, the electric field component leads the magnetic field component by 90°.

LABORATORY STUDIES

The laboratory experiments that are completed and those still in progress are discussed in the following paragraphs. They are grouped in terms of biological area rather than in chronological order of initiation.

Genetics

A study was performed by Coate and Negherbon [5a)] at Hazleton Laboratories in 1969–1970 to determine whether exposure of fruit flies to ELF electric and magnetic fields would induce lethal or semilethal mutations on the X chromosome. The technique used for the isolation of a recessive lethal gene on the X chromosome involves the use of the Muller-5 marker chromosome which carries both dominant and recessive markers. Males were exposed to 20 V/m and 2.0 G at both 45 and 75 Hz. Results of this experiment suggested the action of a domaint lethal mutation. However, if the exposure had caused a dominant lethal, a much higher proportion of recessive lethals and semilethals should have occurred, total fertility should have been lower in the exposed cultures than in the controls, and the number of sterile cultures should have been higher in the exposed cultures than in the controls.

A second fruit fly study was performed by Bender [6a)] in 1971 to evaluate the peculiar results found in the previous study. The protocol was basically the same as before except that the sample size was large enough to detect a weak as well as a strong mutagenic effect. Results of this study led Bender to conclude that there were no genetic aberrations.

In order to increase the certainty that ELF exposure is not mutagenic, a more comprehensive fruit fly study was performed by Mittler [7] in 1972. The Muller-5 stock was not used in this study because it limits the number of genetic aberrations that can be studied. Instead, a multipurpose stock was used. Field levels in this study were 10 V/m and 1.0 G at 45, 60, and 75 Hz. Males were exposed for five days, which is almost half of their reproductive life, and therefore probably all the cells in spermatogenesis were exposed to ELF radiation. Table II presents some data from Mittler's final report. Mittler concluded that there was no induction of sex-linked recessive lethals, translocations between II and III chromosomes, loss of the X or Y chromosomes, nondisjunctions, or dominant lethals. The lethals reported in the initial study by Coate and Negherbon apparently were caused by failure to use virgin females.

TABLE II
DATA FROM MITTLER'S FRUIT FLY STUDY [7] FOR BROOD 1–2 DAYS FROM MALES EXPOSED TO 10 V/m AND 1.0 G AT 75 Hz AND FROM CONTROL MALES

	Exposed		Controls	
	Number	Percent	Number	Percent
yB female	5741	49.28	3795	49.177
+ male	5828	50.02	3847	49.850
y male	49	0.42	48	0.622
Bar female	13	0.111	14	0.181
Mosaic	17	0.145	13	0.168
Total	11 648		7717	
Recessive lethals	1	0.11	8	0.78
Translocations	0		0	
Dominant lethals	63/632	9.9	81/780	10.3

Terms in the first column designate genetic markers. Numbers and percentages for these markers show no significant differences between exposed and controls. In addition, no significant differences are indicated in recessive lethals, dominant lethals, or translocations.

A study was performed by Pledger and Coate [5b)] in 1969–1970 to determine whether ELF fields can induce auxotrophic mutation in a bacterial population. *E. coli* cells were exposed to field levels up to 20 V/m and 2.0 G at 45 and 75 Hz. There was no indication of mutagenic effects on these bacteria.

A cytogenetic analysis of onion root tips was performed by Coate and Hoo [5c)] in 1969–1970. Onion roots were exposed to field levels up to 20 V/m and 2.0 G in water at 45 and 75 Hz. Root cells were examined for polyploidy, anaphase and telophase lags, anaphase and telophase bridges, and other structural anomalies. The investigators found no evidence of chromosomal damage from exposure to the ELF fields.

A more extensive study of chromosomes and cells in plant roots is being conducted by Miller at the University of Rochester. The rate of root elongation, mitotic index, and possible production of chromosomal abnormalities are studied in bean roots exposed to ELF electric and magnetic fields. These parameters are sensitive to stresses well below those usually employed for inducting significant increases in lethality or mutation. If the bean roots are perturbed by exposure to the ELF fields, then an alteration in the rate of root elongation or mitosis would be expected.

Fertility

Another area of study was ELF effects on fertility by Coate and Reno [5d)] in 1969–1970. By encompassing the entire cycle of the rat, the study was designed to assess effects on reproduction potential at any point. Rats were bred and the young reared under constant exposure to field levels up to 20 V/m and 2.0 G at 45 and 75 Hz. The study was continued through the second generation. Mating behavior and conception rates were observed.

Caesarean sections were performed on some females and fetuses were examined for weight, length, and abnormalities. Observations of naturally delivered offspring included sex, mortality, body weight, and anatomical defects. Representative tissues were microscopically examined for pathology. The investigators noted no significant differences in any of these parameters between exposed and control populations.

Physiology

Another field of interest was the possible effect of ELF fields on canine physiology. An initial study was performed on beagle dogs by Teeters and Coate [5e)] in 1969–1970. Parameters were selected on the basis that they would reflect the activity of the major organ systems. Thus, hematological and biochemical determinations of blood and blood serum were made, urinalysis was performed, electrocardiograms and electroencephalograms were analyzed, blood pressure and body weight were measured, eyes were examined, observations of gross appearance and behavior were made, and the animals were necropsied and all major organs and tissues were observed for gross abnormalities. Exposure levels were up to 20 V/m and 2.0 G at 45 and 75 Hz. No effects of the ELF exposure were noted on any of the preceding parameters except for an indication of possible hypertension. Although this effect was inconclusive, a study is now in progress at the Naval Air Development Center to determine whether the increase in blood pressure is caused by ELF exposure or by some other influence, such as confinement. Another study at the Naval Air Development Center is in progress to determine whether exposure to ELF fields affects weight gain of young rats.

Growth and Development

A study of seed germination and early growth in corn, buckwheat, and sunflowers was performed by Coate [5f)] in 1969–1970. Seed germination rate, germination success, and seedling growth at seven days post germination were determined. Exposure levels were up to 20 V/m and 2.0 G at 45 and 75 Hz. Test data showed no effect on any of the parameters measured, but growth retardation of sunflower seedlings was noted. Therefore, a repeat of some of the tests on sunflowers was performed by Rosenthal [6b)] in 1971. A milder retardation effect was observed in these tests.

A more extensive study was performed on sunflower growth by Ruddat [8] in 1972. This study was conducted in the University of Chicago greenhouse. Fig. 1 is a photograph of the ELF field simulators in the greenhouse. Analysis of seven experiments, performed from April through August, showed that the normal variation in temperature, humidity, etc., under *controlled* greenhouse conditions cause more difference in seedling growth than exposure to ELF fields!

At the University of Wisconsin-Madison, metabolism of plants grown under controlled environmental conditions and exposed to ELF electric fields is being studied

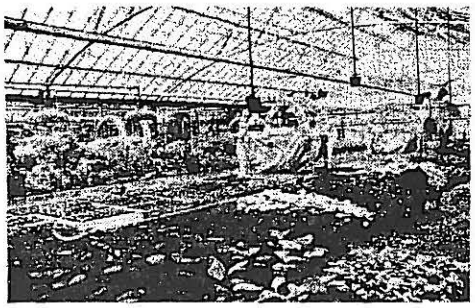


Fig. 1. ELF field simulators in greenhouse for Ruddat sunflower study [8].

by Gardner. One mechanism under investigation is the uptake of water across root membranes and its ultimate influence upon photosynthesis. Other studies include plant transpiration, color, total dry matter production, diurnal rhythms of leaf movements, daily leaf area enlargement, and internodal growth. These metabolic activities were specifically selected because they are sensitive and quantifiable indicators of environmental stress.

Growth and development of slime mold exposed to ELF electric and magnetic fields is another sensitive system being studied by Goodman at the University of Wisconsin-Parkside. The natural habitat of slime mold is at ground level on decaying vegetation. These experiments have been designed to assess the effects of short-term exposure on specific biochemical and physiological processes. These studies also allow an all-important assessment of long-term exposure. Among the parameters being studied are the synchrony of mitosis, reversibility of protoplasmic streaming, and protein synthesis.

Turning to higher organisms, growth and development of chickens exposed to ELF electric and magnetic fields are being studied by Durfee at the University of Rhode Island. The domestic fowl has been selected as the "guinea pig" for three reasons. 1) It is closely related to several wild terrestrial nonmigratory birds (pheasant, grouse, quail, turkey) that are widely distributed throughout the United States. The laboratory results with the fowl will, therefore, have relevance to these species as well. 2) Embryonic development outside the body of the parent and the precocial nature of the chick provide excellent material for the study of early developmental responses. 3) The domestic fowl is not *terra icognita*; rather, it is a biologically very well known laboratory animal. In this study, eggs are being exposed during incubation and the chicks are exposed through sexual maturity.

A parallel study is in progress at the Naval Air Development Center to determine whether exposure to ELF electric fields has any effect on hatchability of frog eggs and viability and metamorphosis of tadpoles. Eggs are exposed to the field in water. Hatchability and time required for hatching and mortality of the tadpoles are determined. Metamorphosis is evaluated by appearance of fore and hind legs, resorption of tail, and appearance of the adult frog.

Behavior

Studies of behavior by Coate [5g)] in 1969–1970 were designed to determine whether various species could perceive ELF fields and respond positively, negatively, or indifferently to them. The test subjects were offered a free choice between staying in or leaving the spatial region in which the ELF fields were introduced. The species tested were fish, turtles, ducklings, rats, dogs, and fruit flies. Each species was tested in its appropriate milieu: soil, water, or air. Coate concludes that an electric field of 10 V/m in either a conductive or a nonconductive medium was insufficient to promote a translocational movement in any of the species tested. A 20-V/m gradient in water may have been close to the threshold.

Learning ability of rats exposed to ELF fields was also studied by Coate [5h)] in 1969–1970. Thirty-day-old rats were used, whose parents had been exposed to ELF electric and magnetic fields for 80 days prior to mating. The pregnant females and the resulting litters were similarly exposed until the pups were tested. A shock avoidance testing apparatus was used in which the test subject had to learn to attain a position on a platform above a grid floor in order to avoid an electrical shock applied periodically through the grid floor. The platform was translated to a vertical position after each trial to dump the rat back onto the grid floor. The investigator found no effect on learning ability in rats exposed *in utero* and then bred and reared in the presence of the ELF fields.

A study was performed by Straub [9] in 1972 to determine the threshold of perception of ELF electric fields in marine animals. The test animals included sea anemone, scallops, snails, crabs, shrimp, sea squirts, croakers, and pin fish. The animals were exposed to the electric fields in natural sea water in laboratory test trays. The threshold level of perception was based on the visual "startle" or "avoidance" reaction of the test specimen. The perception threshold was determined in terms of the current density in the water.Threshold levels ranged from 2 mA/cm^2 for sea squirt to 50 mA/cm^2 for snails. Thresholds observed for these animals are roughly 1000 times greater than Sanguine conceptual levels.

A comprehensive study of behavior in pigeons and rats was performed by Marr *et al.* [10] in 1972. One procedure used to study operant behavior in the pigeon was a temporal discrimination performance task in which differential response was conditioned upon the duration of a stimulus. The stimulus was a key lamp which would be illuminated for discrete durations ranging from 1 to 10 s. If the key lamp were on for 1 to 5 s, a peck on a red key resulted in food presentation. If the key lamp were on for 5 to 10 s, a peck on a green key resulted in food presentation. A peck on the wrong key resulted in a time-out period with no food reward.When the test subject learned to perform the task, ELF electric and magnetic fields were applied to determine if the presence of these fields altered the pigeon's performance. A conditioned suppression technique was used to determine whether rats could detect the presence of the fields. Rats were trained to perform a lever press task for food reward. A flashing light signaled the onset of an electric shock in 1 min. The subject would stop performing when the flashing light occurred, in anticipation of the shock. When a responding pattern was established for the test animal, the ELF fields were substituted for the flashing light to determine the threshold of perception of the fields. A similar technique was used to determine the threshold of perception in pigeons. Pigeons were also used to determine whether they would show preference or avoidance of the ELF fields. Two key lights were available in this task and identical food reinforcement occurred for a response to either key. When a responding pattern was established for an animal, the ELF fields would be applied when the subject responded on one of the keys but not on the other. Marr *et al.* concluded that exposure of the subjects to field levels up to 2 G and 100 V/m at 45, 60, and 75 Hz had no effect on operant behavior. Pigeons and rats did not perceive these fields as shown by results of detection experiments and confirmed by preference procedures.

Two experiments were performed by Grissett *et al.* [11], [12] in 1971 to investigate the reaction time in monkeys exposed to ELF magnetic fields. The experiments were similar except that test subjects were exposed to the fields for short periods of time in one experiment and for long periods of time in the other. Monkeys were trained to perform a task in conjunction with a reinforcement schedule. They were required to depress a lever and hold it in that position for 5 s and release it only during the next 3 s in the presence of a light stimulus. No food reinforcement was given if the lever were released before or after the light stimulus period. Grissett concluded that central nervous system performance, as measured in these experiments, appeared to be insensitive to a magnetic field of 10 G at 45 Hz.

Additional experiments with monkeys were performed by deLorge [13] in 1972. These involved exploration of operant response rates, reaction time performance, a measure of immediate memory, and general motor activity. The fixed interval task required the test subject to raise a response lever in the presence of a green stimulus light and hold the lever up for 20 s, which resulted in the illumination of the food or water receptacle. A press to the button switch adjacent to the lighted receptacle resulted in reward. The reaction time task required the test subject to raise the same response lever in the presence of a red stimulus light and hold it in that position until a tone appeared. The lever had to be released in the presence of the tone, which remained on for only 3 s, in order for the reinforcement receptacle to become illuminated. The immediate memory test involved a match-to-sample task. A disk would become illuminated displaying a symbol by use of rear projection. A finger press to this disk actuated a symbol on a second disk matching the one on the first and also actuated a third disk displaying a symbol that did not match. A finger press to the disk whose symbol matched that of the first disk resulted in food or water reinforcement. The investigator concluded that no significant changes in any of the behavioral parameters measured in this study could

be related to the exposure of 1.4 V/m and 10 G at 75 Hz. These results provide supportive evidence that these specific fields have no general behavioral influence on monkeys.

A study by Adey *et al.* at the University of California-Los Angeles is in progress on neurophysiology and behavior of monkeys exposed to ELF electric fields. The technique involves a series of experiments in which well-trained monkeys perform a demanding "time estimation" task. Some of the test subjects have surgically implanted brain electrodes so that possible direct effect of the fields on brain activity may be detected. Electroencephalograms (EEG's) are recorded while the test subjects are performing the time estimation task. In this way, performance data can be correlated with the EEG recordings to search for indications of subtle effect of the fields on brain activity.

Behavior of fish exposed to ELF electric and magnetic fields is being studied by McCleave at the University of Maine. The subjects are two migratory species; the Atlantic salmon and the American eel. Perception of the applied fields is determined by utilizing the phenomenon of vagus inhibition—the heart rate slows momentarily following certain stimuli such as an electric shock, a loud noise, a flash of light, etc. An electric shock is used as the unconditioned stimulus and an ELF electric or magnetic field is used as the conditioned stimulus to determine the perception threshold for ELF fields. Observations of locomotor activity rhythms are also correlated.

Behavior of chickens exposed to ELF electric and magnetic fields during incubation and up to sexual maturity is the counterpart of the chicken embryology-development study described before. This work is being conducted by Durfee at the University of Rhode Island. Early posthatching behavior is measured by noting balance and coordination, nervousness, responsiveness to heat and light, water and feed acquisition, and preference for feed types. Learning and memory consolidation are examined by using the chick peck test. The effect of ELF on behavior in older birds is determined by observation of social peck order.

Biological Rhythms

A study by Halberg is in progress at the University of Minnesota to investigate whether exposure to ELF fields has any effect on biological rhythms of mice, flour beetles, and silk trees. Some of the biological rhythms being monitored include body temperature, movement, estrus cycle, and susceptibility to drugs.

The Atlantic salmon and the American eel are also being used to study biological rhythms by McCleave at the University of Maine. The major objective here is to determine if locomotor activity levels that are synchronized by a biological clock are affected by exposure in a Sanguine simulated field.

Soil Microbiology

Intact soil samples from a meadow and from a pine the laboratory by Rosenthal [6c)] in 1971. For a period of 16 weeks 1 V/m and 1 G were applied to the samples. Small samples of soil were removed at 0, 2, 4, 8, and 16 weeks. Changes in microbial population were measured by assays of total numbers of aerobic and anaerobic microorganisms and of groups of microorganisms that are known to have specific biochemical functions related to soil fertility, e.g., nitrogen fixing and nitrifying or denitrifying bacteria. Results of this study did not indicate any significant effect of the ELF fields on the concentration of microorganisms in soil, nor any significant alterations in biochemical capability of soil samples.

A study by Gardner is in progress at the University of Wisconsin-Madison to determine whether exposure to ELF electric fields has any effect on solute transport and metabolic activity in representative soil saprophytic and pathogenic bacteria and fungi. Bacterial growth cycles and metabolism are also being studied by monitoring turbidity, viable cells, ATP, and key enzyme systems from the lag phase through the log phase to the death phase.

ECOLOGICAL STUDIES

Forest Species Composition

A survey was performed by Rosenthal *et al.* [14] at the Sanguine North Carolina Test Facility in 1970 to assess whether operation of the facility had any effect on adjacent forest ecosystems. The facility consisted of an overhead transmitting antenna 110 mi long, grounded at both ends, with a transmitter connected at its center. It was operated from 1963 until July 1970. The survey was made in August 1970, to assess flora conditions after 7 years of operation. Forest species composition and pine bud development adjacent to the antenna were studied. Data from the pine bud development survey were compared with data obtained in areas remote from the antenna adjacent to roadway clearings and clearings for an electric power distribution line. No changes which could be related to ELF radiation were observed in species composition of characteristic pine hardwood forests. Forest composition proved to be characteristic for the particular region and age of the forest. Pine bud mortality was greater in areas adjacent to the antenna right-of-way than in areas 100 m farther into the forest. But pine bud mortality was also greater in areas adjacent to the road and power line clearings than in areas deeper in the forest. The investigator concluded that this phenomenon is, therefore, not a Sanguine effect but rather an open area effect. From the evidence in this survey, it was not possible to distinguish any specific effect attributable to ELF electromagnetic radiation.

Forest and Herbaceous Ecosystems

A forest and herbaceous ecosystem survey was performed by Rosenthal [6d)] at the Sanguine Wisconsin Test Facility in 1971. The antenna right-of-way was established in the winter of 1968–1969. The antenna was operated with 10 A of current in the summer of 1969,

150 A from the fall of 1970 until the spring of 1971, and with 300 A since that time. In general, the antenna is energized 5 days per week and 6 h per day at either 45 or 75 Hz. The forest and herbaceous ecosystem data obtained in this survey are intended primarily as a baseline census that can be used to assess the flora at some future time. Quantitative descriptions of forest ecosystems adjacent to the antenna and herbaceous ecosystems within the antenna right-of-way were obtained. Pine bud mortality was also determined adjacent to the antenna. Data were also gathered in similar areas remote from the facility for comparative purposes. The investigator observed that from the evidence in this survey, installation and operation of the antenna has not been detrimental to the composition and structure of natural plant communities in the area.

Soil Animals

A soil organism study has been in progress at the Sanguine Wisconsin Test Facility since 1969. Heinemann and Coate [5i)] took soil samples one time in the summer of 1969 and one time in the summer of 1970. These samples were obtained from a test plot near an antenna ground terminal and from a control plot remote from the facility. A more comprehensive study was begun in the summer of 1971 by Greenberg [15]–[17] and has been continued each summer since then. This comprehensive study utilizes more test and control sites than the initial survey, and soil samples are collected four times at approximately monthly intervals during each summer. The three groups of mites and the springtails surveyed in this study fit fairly well into defined ecological roles: Cryptostigmata and Collembola are primary consumers or prey while Mesostigmata and many Prostigmata are secondary consumers or predators. Together they constitute more than 95 percent of higher soil organisms. Population fluctuations of these soil animals in test and control sites were similar during four summers of study in the initial test and control sites and during two summers of study on the sites chosen in the 1971 study. Comparison of paired plots shows almost every combination of greater, fewer, or equal numbers of mites or collembola, without evidence of a correlation with the ELF electromagnetic exposure. The data provide cogent evidence that the soil arthropod populations are functioning independently of the test facility operation.

Oxygen Comsumption

A study of oxygen consumption and respiratory quotient in five species of animals living in the vicinity of the Sanguine Wisconsin Test Facility was performed by Greenberg [18] in 1972 and 1973. The animals were collected from leaf litter, soil, and rotting logs in the immediate vicinity of the test facility antenna and at locations remote from the antenna. The species were the woodlouse, two species of earthworms, the slug, and the redbacked salamander. An important feature of these animals is their limited mobility. Although this is an obvious attribute of slugs, earthworms, and woodlice, it is also true of the red-backed salamander. Unlike most of its kin, this species is wholly terrestrial and has eliminated the annual migration to water. It confines its range to moist woodland, preferring a rotting log as a feeding and breeding site. Oxygen consumption was measured in a closed manometric system by means of a differential respirometer. The amount of carbon dioxide released during respiration was measured to determine the respiratory quotient. There were no significant differences in oxygen consumption and respiratory quotient between test and control animals. On the reasonable assumption that test populations of all five species have been living in Sanguine-generated fields for four years, it may be concluded that such an exposure has not affected the fundamental process of respiration.

Mammal and Bird Census

A survey by U.S. Forest Service personnel of animals and birds in the vicinity of the Sanguine Wisconsin Test Facility has been in progress during the past several years. The purpose of the survey is to collect a data base to be used to assess the impact on these populations of the facility's operation. The deer population has been surveyed in 1966, 1969, and 1972, and the ruffed grouse population has been surveyed since 1967. Activity of the bald eagle and American osprey has been monitored since 1970. A census of the small mammal population in the area was also made. Surveys are continuing for bald eagle, American osprey, ruffed grouse, and deer.

Bird Migration

The orientation of homing pigeons is under study by Graue at Bowling Green State University. Field trials are held at the Sanguine Wisconsin Test Facility. It is expected that results of this study will provide a measure of the influence of ELF fields on bird migration. Birds are released at the test facility to home on their loft at Bowling Green, Ohio, 500 mi away. This will test for initial orientation in the presence of the ELF fields. Short-distance homing experiments are also performed in which birds reared at the test facility are released at a location remote from their loft. This will test for their ability to home on their loft located in the ELF fields generated by the test facility.

Another bird orientation study is being conducted by Southern at Northern Illinois University. Field trials are held at the Sanguine Wisconsin Test Facility. The study utilizes the inherent preference of sea gull chicks to orient themselves in the direction apparently followed during their first fall migration. The ring-billed gull, used in this study, migrates from Lake Michigan to its winter range in the southeastern United States. Orientation trials are run near the test facility antenna with the transmitter on and with it off to determine whether the ELF fields have any influence on their orientation preference.

HUMAN PHYSIOLOGY AND BEHAVIOR

The Naval Medical Research Unit Number 4 is performing a longitudinal health survey of the Sanguine

Wisconsin Test Facility personnel. The survey's purpose is to establish a medical data base for evaluating whether long-term exposure to the ELF electromagnetic field generated by the facility will cause any detectable changes in exposed personnel. A medical history was established for each person and a comprehensive medical examination is performed each year.

A study is in progress at the Naval Aerospace Medical Research Laboratory to determine whether any psychological or physiological effects occur in persons exposed to ELF fields. The study focuses on the cardiovascular and central nervous systems.

CONCLUSIONS

The Navy has sponsored a wide variety of biological and ecological research related to possible effects of ELF electromagnetic fields associated with a Sanguine system. This research spans at least 35 different organisms, including man, and various biological functions. Some of these investigations have been completed and others are still in progress. Results of some completed studies indicated no ELF effect while others suggested additional areas of research, which have been initiated. The research still in progress is progressively reviewed to determine future directions of the biological–ecological research program. It is the Navy's intention to continue to support the research required to properly assess the biological and ecological impact of a Sanguine system on the environment.

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A Quest for a Controllable ULF Wave Source

JOHN R. DAVIS, SENIOR MEMBER, IEEE, AND JOHN W. WILLIS

Abstract—Natural geomagnetic phenomena indicate that wave generation and amplification processes occur spontaneously in the magnetosphere and may be available under certain conditions to permit the frequency band near 1 Hz to be used for communications. An ionospheric duct provides low-loss propagation for waves in this band to distances of thousands of kilometers, and their large skin depth in seawater permits penetration to several hundred meters below the ocean surface.

Several methods by which the generation of waves in this band might be possible are described. Methods involving the modulation of ionospheric conductivity include the injection of plasma clouds into the ionosphere and heating of the lower E region with powerful radio transmitters. Methods involving nonlinear processes in the magnetosphere include cold plasma injection and very low frequency (VLF)/ultralow frequency (ULF) three-wave interactions.

I. INTRODUCTION

COMMUNICATION to reception terminals submerged hundreds of meters below the ocean surface is an important problem for modern navies. The overwhelming impediment to such communications is path loss due to attenuation in seawater, which alone sets an upper limit upon the frequencies available for this mission. By common consensus, it is presently agreed that a command-and-control communications system for transmissions from shore to submarines at operational depth must employ the frequency band below about 100 Hz. The Sanguine system, presently planned to operate between 40 and 80 Hz in the extremely low frequency (ELF) band, is one manifestation of this consensus. Although the radiation efficiency of the Sanguine antenna is small (about 10^{-4}), path losses over path lengths of thousands of kilometers are only a few decibels, because the earth-ionosphere waveguide effectively confines nearly all radiated power to within 100 km above the surface of the earth. Total loss in seawater to 100-m depth is only about 25 dB at 50 Hz, whereas at very low frequency (VLF) it would be hundreds of decibels.

An alternative low-data-rate system could conceivably operate at an even lower frequency. For example, at about 0.5 Hz, attenuation in seawater to a depth of 100 m would be only 2.5 dB. An ultralow frequency (ULF) communications system operating at this frequency thus would enjoy an advantage of more than 20 dB over even a Sanguine system in the criterion of loss in seawater. For receivers at 300-m depth, which may well be reasonable for foreseeable submarine technology, this advantage would be nearly 70 dB and could outweigh any advantage in information bandwidth possessed by the ELF system. However, it is unlikely that conventional radio transmitting methods would permit this advantage to be achieved in practice, since the efficiency of small antennas varies as the square of frequency. (The same amount of antenna input power at 0.5 Hz would yield at most 40 dB less radiated power than at 50 Hz.) Moreover, the ULF communications system would probably suffer by roughly 20 dB in information rate relative to the Sanguine system. Such a system could not realistically be conceived as a competitor to Sanguine.

There are several interesting aspects to a potential ULF system for information transmission, its highly speculative nature notwithstanding, and these matters all center around a possibility that unconventional means of power amplification and radiation can supplant the commonly pictured earth-based transmitter and metallic antenna structure. A waveguiding principle similar to that which affords ELF waves their low attenuation rate in the earth-ionosphere waveguide also may be exploited for ULF propagation. Observations of naturally occurring ULF waves in the form of geomagnetic micropulsations indicate that they can propagate parallel to the surface of the earth in a duct centered in the ionospheric F region with attenuation of as little as 1 to 2 dB/1000 km [1]. In addition, micropulsations along the direction of the magnetic field between conjugate sites can receive as much as 30 dB amplification from the resident protons in the magnetosphere [2]–[5]. If a mechanism for ULF wave generation can be devised which has a radiation efficiency no worse than 10^{-8}, which the frequency-squared proportionality would suggest is a practical limit at ULF for conventional means of radio frequency (RF) radiation, then a communications system at this low-frequency extreme might be feasible. As will be evident from later discussion, the wave-generation mechanisms currently under consideration are not limited by an inherent efficiency parameter such as that quoted above, but so little is known about them that achievable radiation efficiencies could range as well below those values as above them.

It should be made clear that any realistic prospect of ULF *communications* (as opposed to scientific observations) must rest on the achievement of some exotic means either of generating and emitting ULF waves or of amplifying them after conventional means of generation. Section II following contains descriptions of some suggested methods by which ULF waves may be stimulated artificially. These methods are divided into two types: techniques for modifying the dynamo currents which flow naturally in the lower ionosphere and techniques for bringing about and controlling interactions between

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TABLE I
ARTIFICIAL ULF STIMULATION METHODS

Modulation of Lower Ionospheric Conductivity
Cesium plasma cloud injection
Radio frequency heating
Stimulation of Nonlinear Processes in the Magnetospheric Plasma
Lithium cold plasma injection
VLF three-wave interaction

electromagnetic waves and the magnetospheric plasma. We have excluded conventional radiating systems for ULF waves, because they are treated by Fraser-Smith *et al.* [6] and Greifinger [7]. Table I indicates the two types of ULF stimulation methods we shall consider below, and the two classes of experiments by which each type may be investigated. One experiment of the former type involves the injection of ionized gases into the ionosphere, thus modifying the electrical conductivity of that region and so altering locally the magnitude and direction of the ionospheric dynamo currents. Other experiments use ionospheric heating produced by powerful, earth-based RF transmitters in the high frequency (HF) band to bring about changes in ionospheric conductivity or to create perturbed electric fields in the ionosphere, either of which may lead to modification of the flowing dynamo currents. Methods of bringing about wave–particle and wave–wave interactions in the magnetosphere are treated briefly and qualitatively. They have been discussed superficially in the open scientific literature, but no experimental evidence exists on which reliable quantitative estimates of their effectiveness as ULF wave-generation techniques can be based. The lithium cold plasma injection method is treated elsewhere by Liemohn [8] and Cornwall [9].

II. ARTIFICIAL STIMULATION METHODS

Modification of Lower-Ionosphere Currents

The most direct method of modifying the lower ionosphere artificially would involve deposition of an ionized gas into an appropriate volume of the E region, such as an altitude where strong background electric currents flow, thereby providing the means of coupling to the geomagnetic field. Such currents flow in the region between 100 and 140 km, where the electrical conductivity tensor is anisotropic. At these altitudes the Hall and Pedersen conductivities cause a maximum to appear in the transverse conductivity component (that component of the conductivity tensor which relates to current flowing perpendicular to the direction of the magnetic field and which, for temperate latitudes, is largely horizontal). The current which flows in this region is the familiar ionospheric dynamo current, and it undergoes a relatively regular diurnal cycle, with peaks in midmorning and midafternoon (in opposite directions) and with nulls at noon and at night. For a given percentage change in electrical conductivity such as might be achieved by an ionospheric chemical release using an ionizable gaseous material, the most attractive times of day for an experiment would be the times of maximum overhead current flow at the launch site. These currents are of greater magnitude in the summer season at temperate latitudes than at other times of the year, so such an experiment should be conducted as near midsummer as possible.

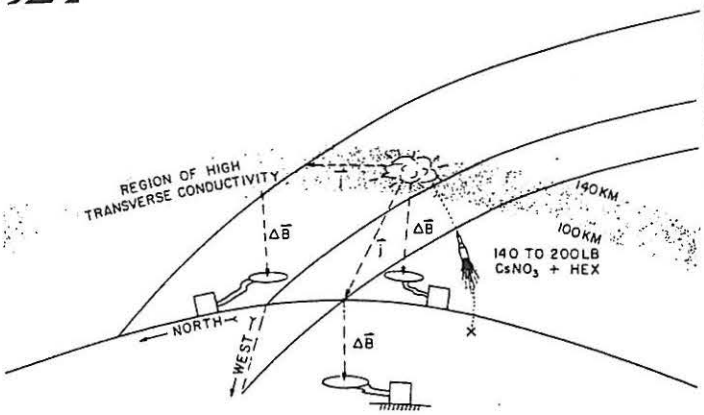


Fig. 1. Sensor network and launch geometry for an experiment to investigate modulation of lower ionospheric conductivity by explosive injection of a plasma cloud. A typical sounding rocket payload of cesium nitrate ($CsNO_3$) and a high explosive (HEX) is depicted as detonating in the ionospheric dynamo region.

An attractive method of plasma-cloud deposition involves detonation of a mixture of a cesium salt and a high explosive. A small fraction of the cesium payload is ionized in this reaction (much less than 1 percent) but it possesses a number of important features. 1) Cesium is thermally ionized in the detonation process, and hence a very large "pulse" of ions is available immediately [10]. The effect on the ambient currents thus should be visible as a large transient and is not likely to be confused with the normal magnetic field fluctuations which occur regularly with periods of tens of seconds. This feature is particularly important, inasmuch as the sensing devices which are most sensitive in the frequency range of interest (0.5 to 5 Hz) are induction devices. They are thus sensitive to the rate of change of the magnetic field, and a method which maximizes the rate at which plasma interaction with the geomagnetic field takes place is most attractive. 2) The energy imparted to the cesium cloud in the explosion propels the outer boundaries to a large distance, and the speed with which the charged spherical volume expands enhances the interaction of the plasma cloud with the constraining background magnetic field. 3) The hydrodynamic time scale of the lower E region is well suited to the electromagnetic time scale of interest [11]. The plasma cloud expands and undergoes reverberation over a time scale of a few tenths of seconds to several seconds, depending on altitude. Consequently, it would be expected that the product of the interaction between the plasma cloud and the ambient currents would be characterized by a wave spectrum in the frequency band of interest.

Fig. 1 is a sketch of such an experiment. The stippled band represents the ionospheric dynamo region at 100 to 140 km altitude. Shown schematically are three geomagnetic field lines passing through the ionosphere and forming an orthogonal set of axes in geomagnetic co-

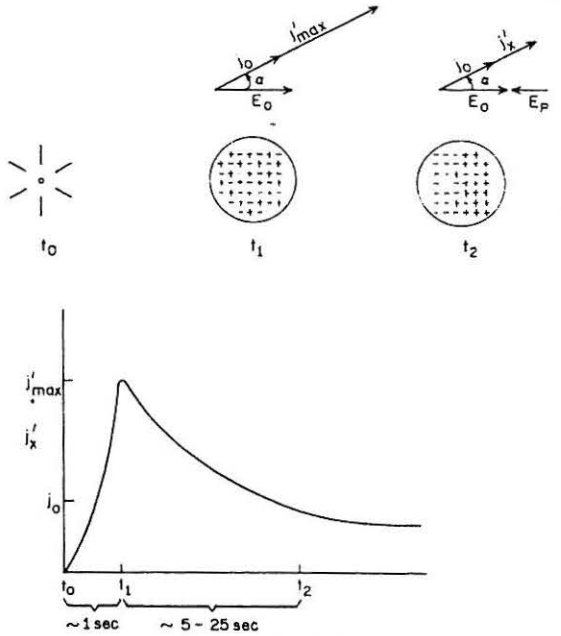


Fig. 2. Pictorial representation of the three stages of plasma cloud growth, with a sketched graph of the calculated behavior of the perturbed ionospheric currents.

ordinates where they intersect the ground (they define north–south and east–west geomagnetic planar surfaces). A rocket conveying the cesium salt and high explosive (in this case, cesium nitrate and TNT in a payload of 140- to 200-lb net weight) is launched from the ground and detonated in the dynamo region. Disturbance current vectors j are shown emanating from the plasma cloud region, and these disturbance currents give rise to geomagnetic fluctuations ΔB which can be detected on the ground by suitable sensors. In the experimental configuration envisioned, sensors can be placed both directly beneath the burst region and away from it in both the north–south and east–west planes. Thus the source field near the burst point and wave components traveling horizontally in the directions of the orthogonal axes can be detected. Fig. 2 illustrates the processes which we envision in an idealized model. Beginning at t_o, an explosion takes place in which both charged and neutral particles are driven by the thermodynamics of the explosion to form a nominally spherical ionized cloud in pressure equilibrium with the environment. At time t_1 the ionized cloud begins to experience charge separation due to the background electric field E_o and continues under this influence for approximately the interval in which a charged particle drifts across the cloud. At time t_2 the polarization electric field E_p has formed across the cloud, and for large density perturbations this field limits the perturbed current in the x direction (the direction of background current streamlines) to approximately the value of the undisturbed current j_o. The maximum value of the perturbed current j_x', which is achieved at t_1, is given over the volume of the cloud by

$$j_{max}' = \frac{N' - N}{N} (\sigma_1^2 + \sigma_2^2)^{1/2} E_o$$

where N' is the electron density in the ionized cloud, N is the background electron density, and σ_1 and σ_2 are the Pedersen and Hall conductivities, respectively. For the point on the ground a distance z_1 directly below the plasma cloud, assuming $\sigma_2 \gg \sigma_1$ in the lower E region, the disturbance magnetic field is

$$B'(-z_1) \approx \frac{\mu_o}{4\pi} \frac{V_c}{z_1^2} \left(\frac{N' - N}{N} \right) \sigma_2 E_o$$

where V_c is the volume of the ionized cloud.

Assuming typical ionospheric parameters,

$N' = 10^3 N$ (for a cesium release)
$\sigma_2 = 6 \times 10^{-4}$ mho/m (daytime maximum value)
$V_c = 10^{10}$ m^3 (appropriate for a 50-kg payload at 100 km)
$E_o = 10^{-3}$ V/m
$z_1 = 10^5$ m

yields $B' \approx 10^{-11}$ Wb/m^2 $= 10^{-2}$ γ.[1] This quantity is at the lower limit of sensitivity for total field measuring devices. Because the likely field instrumentation consists of induction sensors, a more appropriate quantity would be the time rate of change of the perturbation field, dB'/dt. Since hydrodynamic considerations indicate that the time scale of plasma-cloud expansion should be not greater than a few seconds, the quantity dB'/dt is likely to exceed several milligamma per second and is probably detectable with large loops of the kind used for the most sensitive geophysical observations. It is less likely, however, that remote sites would be able to detect an attenuated version of this perturbation, if indeed this perturbation is effective in stimulating a ducted wave. Though attenuation in the ionospheric waveguide is small, the portion of the disturbance field which is converted into such a wave is undoubtedly only a fraction of the total field magnitude. It is suggested by this calculation that chemical releases in the temperate zone lower ionosphere can permit, with present sensor technology, confirmation of the hypothesis that such means are capable of causing a significant disturbance in lower ionosphere current flow. A modest effort is probably worthwhile simply to achieve this goal. An initial experiment in this direction produced an apparent local fluctuation on the order of 10 mγ [12]. The greater objective of measuring the ducted ULF waves which may be emitted by such a disturbance probably can be met only if a magnetospheric amplification process for ULF waves can be exploited, or if vehicles capable of lifting orders of magnitude larger payloads are used.

A second method of bringing about fluctuations in lower ionosphere currents involves varying either the E-region electrical conductivity or the ambient dynamo currents by means of an indirect method, such as the collection of techniques known as "ionospheric heating." The first obvious candidate for changing E-region con-

[1] The geomagnetic variations are given in conventional geophysical units. One γ is equal to 10^{-9} T.

ductivity would employ a high power RF heater operating at typical lower-E-region plasma frequencies. In order to be useful during the 1000 to 1400 local mean time (LMT) period in which dynamo current strengths are highest (and, hence, in which a given proportionate change in conductivity would lead to the greatest absolute fluctuation in local magnetic field strength), the transmitter must operate in the 1.5 to 3.0 MHz frequency range. However, radio waves at these frequencies undergo considerable nondeviative absorption in the D region in daytime, and it may not be possible with realizable transmitter power capabilities to heat the daytime E region by plasma-resonance heating.

An alternative to plasma-resonance heating of the E region might be electron gyroresonance heating, in which the transmitter frequency would be matched to the frequency at which electrons gyrate about the magnetic field direction. Such a method would have the advantage that the transmitter could be built to operate at a single frequency, which for midlatitudes would be near 1.5 MHz. It would suffer the same daytime penalty of high D-region absorption as the plasma-resonance method.

An intriguing possibility which avoids large D-region losses involves the phenomenon of sporadic E. Sporadic-E layers form in a largely unpredictable manner, but principally they form in the daytime at midlatitudes and preferentially in the summer months. They are characterized by plasma frequencies of as much as 10 MHz (and even higher values on infrequent occasions), extend over areas of 10^{11} to 10^{12} m^2, and are located in the vicinity of 100-km altitude. It is likely that such layers, due to their high electrical conductivity, carry a large proportion of the local dynamo current and hence are attractive targets for artificial stimulation of ULF waves. For example, to achieve a perturbation magnetic field equal to that which was calculated previously for a cesium plasma cloud volume of 10^{10} m^3, a typical intense sporadic-E layer having a volume of 10^{15} m^3 would require a rapid electron density variation of only about 1 percent. A fractional electron density change of 1 percent over a volume of 10^{15} m^3 (equivalent to a 10 km thick sporadic-E layer of about 300 km lateral extent) might be achievable by RF heating. Heating an intense sporadic-E layer by the plasma-resonance technique would be possible at frequencies well above the range in which daytime D-region absorption is severe, and hence the main drawback of this method for E-region heating would be avoided.

This method of altering dynamo current flow might also be of interest in northern latitudes, where the phenomenon of "night E" is common [13]. Often called high-latitude sporadic E, such layers of high charged particle density in the nighttime E region might present an opportunity to combine the excitation of ULF perturbations in the lower ionosphere with access to the magnetospheric amplifier and to the low attenuation of ducted waves in the ionospheric waveguide. Moreover, the occurrence of night E is rather more prevalent (and predictable) than is midlatitude sporadic E and would permit experiments to be conducted with less uncertainty regarding the probable adequacy of ionospheric conditions.

Recent experiments by Showen [14] have demonstrated that nondeviative absorption can be exploited to cause substantial heating of the lower ionosphere with transmitter frequencies well above the local plasma resonance frequency. The temperature of the electron gas increases because electrons are slow to dissipate energy acquired from the wave through collisions with the more massive neutrals and ions. This rise in electron temperature has two principal consequences: 1) it alters their chemical reaction rates with the ambient ionic species; and 2) it results in expansion of the ambient plasma and concomitant reduction of density in the heated region. Calculations by Gurevich [15] indicate that in the lower ionosphere (heights less than 200 km) the decrease in the electron recombination coefficient dominates, leading to a density increase. Near the F-layer maximum (300 to 400 km) the key factor is the plasma expansion, which leads to a density decrease. In the E region, for a typical daytime plasma frequency (2.8 MHz), the density increases on a time scale of 15 seconds and grows asymptotically to one-half the percentage change in electron temperature [15], [16].

A high power RF heater which is capable of sustained continuous wave operation is located near Boulder, Colo. [17] and operates over the band from 2.7 to 10 MHz. In a previous paper [18], which can be consulted for details, we presented a treatment of nonresonant absorption heating using the parameters of that transmitter and applied to the problem of perturbing the ionospheric dynamo currents. In that work we began with Showen's [14] nonresonant absorption heating calculation to determine the temperature increase and followed it with an application of LeLevier's [16] method for determining density variations from a temperature-dependent recombination coefficient. Taking into account the propagation anisotropy introduced at HF due to the magnetoionic effect and the D-layer absorption that is important in the lower HF band, we found that right-hand circularly polarized radiation in the daytime, at frequencies between 5 and 10 MHz can give rise to temperature changes of 2 to 33 percent in the 90–120 km altitude region with time constants of 8 to 90 seconds.

In more recent, unpublished work, we have included explicitly the temperature dependence of the collision frequency and the excess electron energy loss coefficient. This refinement results in increased energy absorption both at the height of interest and in the D region. It is important because recent results of Jones and Davies [19] indicate that heating with the Boulder transmitter may cause significant increases in electron temperature in the D region. In addition to this improvement, we have accounted for resonant absorption by using the Wentzel–Kramer–Brillouin (WKB) approximation. We still have assumed vertical incidence. Some further reduction in absorbed energy would be expected due to refractive spreading of the oblique rays [20], but we have not

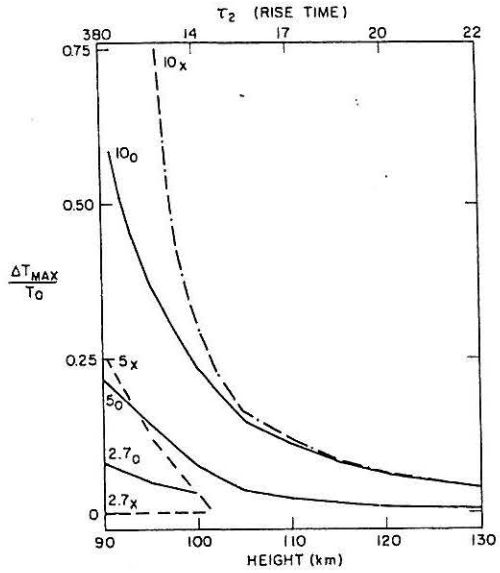


Fig. 3. Calculated ionospheric heater-induced temperature changes (ΔT_{max}) and characteristic time scales of electron density variation (τ_2) in the ionospheric dynamo region for heating transmitter frequencies of 2.7, 5, and 10 MHz in the daytime in sunspot minimum conditions. Results are shown for both ordinary (subscript o) and extraordinary (subscript x) transmitted polarizations. The E-region critical frequency is 2.8 MHz.

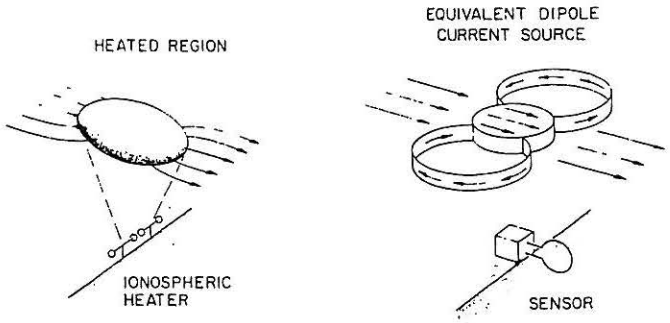


Fig. 4. (a) Pictorial representation of ionospheric currents disturbed by heating transmitter. (b) Equivalent dipole current source used for calculations of ionospheric heating effect on the local geomagnetic field. The sensor loop is oriented to intercept magnetic flux from the dipole.

treated that phenomenon. We have constructed from a variety of sources [21]–[23] a model ionosphere appropriate to the Boulder transmitter latitude at sunspot minimum for the daytime, nighttime, and twilight (0600 LT). Using the Cospar International Reference Atmosphere [24] for the neutral constituents, we have computed the perturbed temperature and density for the E region above the Boulder transmitter at different frequencies and polarizations. Representative results are illustrated for the daytime case in Fig. 3. Three frequencies are included in Fig. 3, with an ordinary (subscript o) transmitted wave polarization case shown as a solid line, and an extraordinary (subscript x) case shown as a dashed line. The E-region critical frequency was 2.8 MHz, and so the 2.7 MHz cases in Fig. 3 represent the results for resonant absorption heating. At heights below 96 km (in the 10-MHz case) the temperature increase for the extraordinary (left-hand polarized) mode exceeds the assumed small perturbation. We have listed at the top of the graph time constants for density growth appropriate to the corresponding heights on the abscissa.

From these calculations it appears that resonant heating is not effective in the E layer due to the large losses in the D layer as the heating frequency is lowered. The power available for absorption heating in the E layer is reduced by the *integrated* absorption in the D region. At the higher end of the 2.7–10 MHz band, the extraordinary mode is the more effective heater. Despite actual lower heating efficiency in the daytime due to losses below the E region, magnetic variations in the Pc 1 band[2] are more likely to be achieved in the daytime because of the smaller time constants involved (the growth time is inversely proportional to electron density) and the higher daytime dynamo currents.

It is generally accepted that by far the greatest contribution to the atmospheric dynamo current flow takes place in the E region. We have illustrated in Fig. 4 our conception of the effect of a localized electron density change in the E region upon the dynamo currents. Increasing the electron density, as we have indicated should be possible with a suitable ionospheric heater, causes a concomitant increase in electrical conductivity (principally the Hall component) in the heated region. The dynamo current thus tends to be enhanced in the heated volume, as we have shown in Fig. 4(a) by concentrating the flow of current streamlines through this region. The changes of dynamo current flow which occur as the transmitter is switched on and off should be visible as cyclic changes in the dynamo-associated magnetic field at the earth's surface. Fig. 4(b) shows a model dipole current source for the heated region that we have used for calculations. In this model the heated region is treated as a cylindrical electric dipole, superimposed on the background dynamo current streamlines.

To obtain an indication of the degree to which the changes in E-region charged particle density we have calculated might lead to magnetic field variations, we have adapted a model first described by Martyn [25], and it is this model which is represented in Fig. 4(b). The details of the treatment appear in Willis and Davis [18], and once again we shall simply state the conclusions. Assuming a background electric field of 10^{-3} V/m and a heated ionospheric volume at 100-km altitude of 10-km thickness and 30-km diameter, we have listed in Table II the change in E-region electron density $\Delta N/N$ and magnetic perturbation on the earth's surface ΔB which would arise from several heater pulselengths at an assumed interaction altitude of 100 km. Data are included for three times of day and two polarizations. Extraordinary polarization seems to be most effective under all conditions, but in many cases the linear perturbation method

[2] The Pc 1 band is defined as the frequency range 0.2–5 Hz.

TABLE II
ESTIMATED RESULTS OF HEATING AS A FUNCTION OF TIME OF DAY, POLARIZATION, AND TRANSMITTER PULSE LENGTH

Model Ionosphere	Day		Twilight		Night	
Time constant τ_2 (sec) @ 100 km	14		331		527	
Frequency (Polarization)	$(10\ MHz)_o$	$(10\ MHz)_x$	$(10\ MHz)_o$	$(10\ MHz)_x$	$(10\ MHz)_o$	$(10\ MHz)_x$
$\Delta T_{max}/T_o$	22.5%	30.3%	39.7%	NL*	55.3%	NL*
$[\Delta N_e/N_e]$ 60 sec pulse	11%	15%	3.3%	NL*	3.0%	NL*
$\Delta B(m\gamma)$	7	8	.1		.1	
$[\Delta N_e/N_e]$ 10 sec pulse	5.8%	7.8%	.6%	NL*	.5%	NL*
$\Delta B(m\gamma)$	5	6	—		—	
$[\Delta N_e/N_e]$ 1 sec pulse	.8%	1.1%	.1%	NL*	.1%	NL*
$\Delta B(m\gamma)$	1	1	—		—	

*NL refers to modes where the perturbed temperature is too large to be treated with the linear theory.

was inapplicable because of the extremely large change in ionospheric temperature.

An inherent advantage of the ionospheric-heating type of experiment over the chemical-release technique discussed previously is the greater control which can be exercised over experimental parameters. In the chemical release experiment, the ULF wave is essentially transient, and sensors must correspondingly maintain a bandwidth adequate to pass the entire spectrum of the transient signal. This bandwidth may be several hertz. In the case of the ionospheric-heating experiment, the forced response of the ionosphere is controllable by the modulation parameters of the heating transmitter, so long as the ionosphere will accommodate the appropriate wave spectrum. Although the transient response of the ionospheric medium will be superimposed on the desired signal spectrum, signal-processing techniques can be used to discriminate in favor of the forced response frequency. Allowable predetection signal bandwidths then are controlled only by the fluctuation spectrum of the ionospheric medium and can be made as narrow as this parameter will allow. Cross-correlation processing times of hundreds of seconds (bandwidths of thousandths of hertz) may be possible, and a signal-to-noise ratio advantage relative to the chemical-release case of several tens of decibels might be achievable. Such cross-correlation signal processing could be readily accomplished by simply comparing the band-limited ULF sensor output to a suitably demodulated replica of the transmitter waveform. This operation could be performed in the laboratory from data recorded on magnetic tape. The use of coherent integration is of particular importance for two reasons. It is necessary to place the magnetometer far enough away from the heater that the influence of the heating transmitter on the power mains, or of inadvertently radiated fields at the pulse repetition frequency, does not contaminate the magnetometer signal. The perturbed magnetic field at a suitable remote site will be reduced below the maximum value. Furthermore, it will be of interest to employ a pulse cycle much shorter than the optimum length of about 20 seconds, in order to investigate the *Pc* 1 micropulsation band. Induction antennas, which might be used to receive the magnetic perturbation, have a frequency-proportional sensitivity characteristic, and are most effective at frequencies above 1 Hz. Thus, heating cycles of one second and shorter may be desirable.

We are engaged in a series of experiments to test the concept of employing the Boulder heater to perturb the dynamo currents. The results thus far have not produced magnetic perturbations of the predicted magnitudes, however narrow-band analysis may yet reveal a detectable signal.

Stimulation of Wave–Particle and Wave–Wave Interactions in the Magnetosphere

There are two types of interactions involving stimulated emission of ULF waves in the magnetosphere which could be investigated. The methods employed to achieve this stimulation bear a superficial resemblance to the two general types of stimulus described above—one of them involves injection of charged particles and the other involves use of a high power radio transmitter. In both cases, however, the principle involved is quite different from those described previously. Whereas in the prior examples the techniques resulted essentially in the creation of a radiating system by modulating current passing through a more-or-less linear equivalent circuit, in the present cases both methods involve the exploitation of a nonlinear property of the trapped-proton belt.

Based on the presumption that *Pc* 1 micropulsations result from the spontaneous response of a latently unstable energy/pitch-angle distribution of protons in the near-equatorial magnetospheric region [2]–[5], it might be possible to artificially inject charged particles into the magnetosphere in sufficient quantity to stimulate the instability. The likelihood that such an endeavor would succeed in distorting the overall energy/pitch-angle spectrum (that of the resident particles plus the added ones) and thus give rise to the desired emissions is discussed by Liemohn [8] and Cornwall [9].

Estimates based on present knowledge of the resident proton population indicate that several kilograms of

ions injected into the appropriate magnetospheric region might suffice to create the desired condition of instability [8],[26]. For this operation to cause amplification of waves in the 0.5- to 5-Hz band, the ionic species must be a light one, and lithium would be an attractive choice. The material could be ejected from a rocket or satellite launched into the precise desired position, which would require a high trajectory and consequently a large and rather sophisticated vehicle. Alternatively, it could be injected at relatively low altitude (just above the collision-dominated region of the atmosphere, so that the injected material would not be impeded by local particles) by a shaped charge or ion beam generator oriented along the direction of the geomagnetic field. The latter method has appeal because the charged beam would be collimated by the magnetic field and hence could be confined to the desired magnetic field lines. It is not known whether lithium or other light ion beam generators could be constructed to deliver a large enough number of ions, and the ion-beam method is likely to be expensive.

Measurement of the effects of this plasma injection operation on ULF waves would involve a slightly more complicated arrangement than has been described in the preceding. Instrumentation should be located at both terrestrial terminals of the geomagnetic field lines along which the plasma is injected, and orthogonally displaced sensor networks should be established in at least one of these terminal regions. Baselines should be much longer than in the previous examples, because of the larger probable geographical extent of the effects, and a larger number of stations should be used. The initial experiment should probably be conducted under darkened conditions at both terminals to reduce the number of experimental variables, and so a near-equinox period would be appropriate. Observations should show an increase in micropulsation activity coincident with the entrance of the plasma cloud into the equatorial magnetosphere. Once again, as in the case of the chemical releases described previously, the desired signal will be a transient-like manifestation of the free response of the system (although in this case it may be an extended sequence of pulses due to the regenerative properties of the magnetospheric amplifier and its transmission lines terminated in the ionosphere). Sensors should be arrayed so that this signal may be distinguished from background micropulsation noise.

Under certain circumstances, it may be possible for energy to be coupled not only between gyrating particles and MHD waves but between waves of different types in the magnetosphere [27]–[29]. For example, a three-wave interaction could involve two VLF waves (which might be considered analogous to the "pump" and "idler" waves in a laser or parametric amplifier) interacting to yield a wave at the difference frequency (the "signal"), which might fall in the ULF band. Such an interaction would require very high pump-wave field strengths in the interaction region, and it is precisely for this reason that VLF pump and idler waves are proposed.

The virtue of employing a VLF pump and idler, provided the antenna requirements can be met, is that the magnetospheric trapped-electron belt causes amplification of VLF waves in a manner directly analogous to that described previously in which trapped protons (or ions) can amplify ULF waves. Furthermore, a process of ducting along the magnetic field by field-aligned filaments of charged particle density enhancement has been found both theoretically and experimentally to act as a most efficient means for directing VLF power along the magnetic field between the lower ionosphere and the trapped-particle belt [30].

Consequently, it may be possible to transmit VLF pump and idler waves of the proper polarization from below the ionosphere into field aligned ducts which will direct them into the region of the magnetosphere where they can be amplified by electron cyclotron interactions with trapped electrons. The amplified VLF waves may then exceed the threshold for commencement of a three-wave process whose product will be the desired ULF signal. This signal, which may undergo further amplification due to cyclotron interaction with the resident protons, can then descend to the earth through a series of interactions analogous to those which are appropriate to *Pc* 1 micropulsations and be detected by earth-based sensors. Because the VLF transmitter is controlled, coherent integration may be used for signal processing, with a predetection bandwidth narrowed about the modulation spectral peak (the difference frequency between pump and idler) to as narrow a passband as the propagation medium and operational considerations will allow. Bandwidths of thousands of hertz would seem to be allowed because VLF magnetospheric ducts normally have lifetimes of [illegible] minutes. There is evidence, albeit slim, that three-wave interactions may occur naturally. For example, Fraser-Smith [31] has suggested that atmospheric discharges may be a cause for *Pc* 1 micropulsations, and if so, a three-wave interaction could be the coupling mechanism.

It is of interest to examine the means by which a VLF–ULF three-wave interaction experiment might be conducted. To bring about magnetospheric amplification of VLF pump and idler waves, so that the relatively weak fields of earth-bound transmitters may be increased to the magnitude which is necessary to trigger the interaction, it is necessary to consider the typical frequency ranges in which such amplification is observed naturally and to investigate the sites of available VLF transmitters. According to Liemohn [3], VLF whistlers are most commonly observed at between 3/10 and 5/10 of the equatorial electron gyrofrequency (ω_{ce}) on the magnetic field line which passes through the ionospheric entry point of the whistler. For *Pc* 1 micropulsations the frequency range is between 3/10 and 7/10 of the equatorial proton gyrofrequency (ω_{ci}) along a similarly defined magnetic field line. Assuming an earth-centered dipole as a crude approximation to the magnetic field of the earth, these gyrofrequencies are related to geomagnetic latitude λ

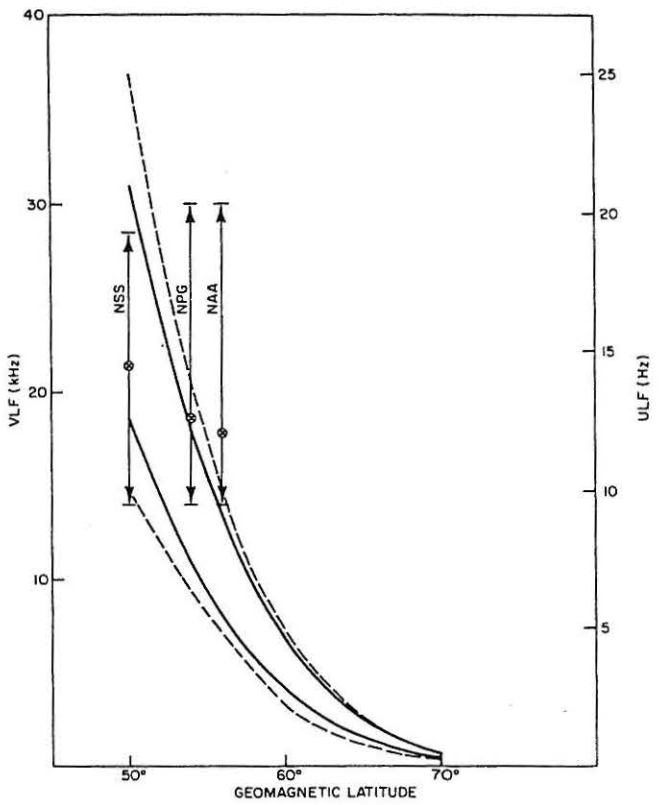


Fig. 5. VLF transmitter frequencies (solid lines and left-hand scale) and ULF modulation frequencies (dashed lines and right-hand scale) appropriate for the magnetospheric three-wave interaction experiment. Tuning bands and operating frequencies are shown for three U. S. Navy transmitters between 50° and 60° North Geomagnetic Latitude. At a given latitude, an appropriate VLF carrier frequency falls between the two solid lines, and an appropriate ULF modulation frequency falls between the two dashed lines.

on the earth by

$$\omega_{ce} = 5.5 \times 10^6 \cos^6 \lambda$$

$$\omega_{ci} = 3.0 \times 10^3 \cos^6 \lambda.$$

Fig. 5 illustrates the frequency bands in which VLF and ULF amplification might be possible under these conditions versus geomagnetic latitude, with ULF frequencies on the right-hand scale. The latitudes, available tuning ranges, and normal transmitting frequencies of three U.S. Navy VLF stations (NPG, NAA, and NSS) are shown superimposed on the curves. Although the tuning ranges available to NPG and NSS include a substantial part of the amplification band, only NSS has a normal operating frequency within this band. NPG and NSS are at such low latitudes that the favored ULF frequencies are above about 7 Hz. This combination of circumstances would favor station NAA as a candidate for an experiment, and experimental effort is underway with NAA as a VLF wave source.

III. SUMMARY AND CONCLUSIONS

If future submarine technology requires communications from shore-based transmitters to receiving stations at several hundred meters depth, the ULF band will have an advantage of about 70 dB relative to the proposed ELF system in attenuation due to seawater. In addition, under the conditions of geophysical variability which follow large solar eruptions and high-altitude nuclear explosions, communications via ELF may be significantly disturbed [32]. Under these conditions, a ULF system may be capable of restoring partial communications.

Two general results from the study of natural geomagnetic phenomena have made it attractive to consider the ULF band as a candidate for a communications system. Geomagnetic micropulsations have been found to undergo a natural amplification process in the magnetosphere which it may be possible to exploit and which may provide up to 30 dB enhancement of signal amplitude. Furthermore, it has been found that micropulsations which impinge on the ionosphere after traversing this magnetospheric amplifying region then propagate in an ionospheric duct which is characterized by an attenuation rate as low as 1 to 2 dB/1000 km. It thus may be possible for electromagnetic energy to reach the surface of the earth over regions thousands of kilometers in extent with very low spreading loss. We have selected a number of candidate mechanisms which seem to involve the most likely means of stimulating the ionosphere and magnetosphere in the frequency band of interest. These means are divided into two basic approaches: 1) modulating the naturally flowing electric currents in the ionosphere and thus coupling energy into the magnetic field; and 2) driving the magnetospheric amplification region into a regenerative state and thus giving rise to micropulsation-like "oscillations," which may be controllable.

We have described two methods by which the former approach may be implemented. One of these methods involves the deposition of an ionized gas into the highly conducting region of the lower ionosphere. We have shown by calculations that this method, employing a few tens of kilograms of cesium nitrate plus a high explosive, can cause a transient magnetic field fluctuation of about 10 mγ/s on the surface of the earth below the disturbed ionospheric region.

We have also described techniques by which RF heating of the ionosphere causes modulation of the ionospheric electric currents. Calculations have indicated that magnetic field fluctuations on the earth of several milligammas also can be stimulated by this means. Because a radio heating transmitter can be modulated at a controlled rate for arbitrarily long periods of time, coherent integration techniques can be used to enhance the geomagnetic field variations relative to noise and thus should permit high signal-to-noise ratios to be achieved. A series of experiments has been begun to test the thesis that RF heating can produce detectable magnetic perturbations, and results thus far are not encouraging.

We also have described two means by which the magnetospheric amplifying region might be caused to generate ULF waves. One such means involves the injection of an ionized gas into the magnetosphere at a distance of several earth radii above the equator, and the other one involves stimulation of a three-wave interaction by transmission

of strong VLF pump and idler waves into the magnetosphere by a whistler mode. Both of these mechanisms involve nonlinear processes in the magnetosphere, and we have described them only qualitatively. An experiment using a U. S. Navy VLF transmitter in an attempt to stimulate three-wave interactions in the magnetosphere is in progress.

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John R. Davis (SM'74), for a photograph and biography, see this issue, page 492.

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John W. Willis was born January 7, 1945, in Guelph, Ont., Canada. With the exception of one year at the University of Gottingen, Germany, his education was received at the University of California, Riverside, where he obtained a Ph.D. in physics in 1971. His thesis research was performed on the Tonks-Dattner resonances, a problem in laboratory plasma physics.

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Dr. Willis is a member of the American Geophysical Union, the American Association for the Advancement of Science, and the American Association of Physics Teachers.

United States Patent [19]

Eastlund

[11] **Patent Number: 4,686,605**

[45] **Date of Patent: Aug. 11, 1987**

[54] **METHOD AND APPARATUS FOR ALTERING A REGION IN THE EARTH'S ATMOSPHERE, IONOSPHERE, AND/OR MAGNETOSPHERE**

[75] Inventor: **Bernard J. Eastlund**, Spring, Tex.

[73] Assignee: **APTI, Inc.**, Los Angeles, Calif.

[21] Appl. No.: **690,333**

[22] Filed: **Jan. 10, 1985**

[51] **Int. Cl.**[4] **H05B 6/64**; H05C 3/00; H05H 1/46

[52] **U.S. Cl.** ..... **361/231**; 89/1.11; 380/59; 244/158 R

[58] **Field of Search** ..... 361/230, 231; 244/158 R; 376/100; 89/1.11; 380/59

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Primary Examiner—Salvatore Cangialosi
Attorney, Agent, or Firm—Roderick W. MacDonald

[57] ABSTRACT

A method and apparatus for altering at least one selected region which normally exists above the earth's surface. The region is excited by electron cyclotron resonance heating to thereby increase its charged particle density. In one embodiment, circularly polarized electromagnetic radiation is transmitted upward in a direction substantially parallel to and along a field line which extends through the region of plasma to be altered. The radiation is transmitted at a frequency which excites electron cyclotron resonance to heat and accelerate the charged particles. This increase in energy can cause ionization of neutral particles which are then absorbed as part of the region thereby increasing the charged particle density of the region.

15 Claims, 5 Drawing Figures

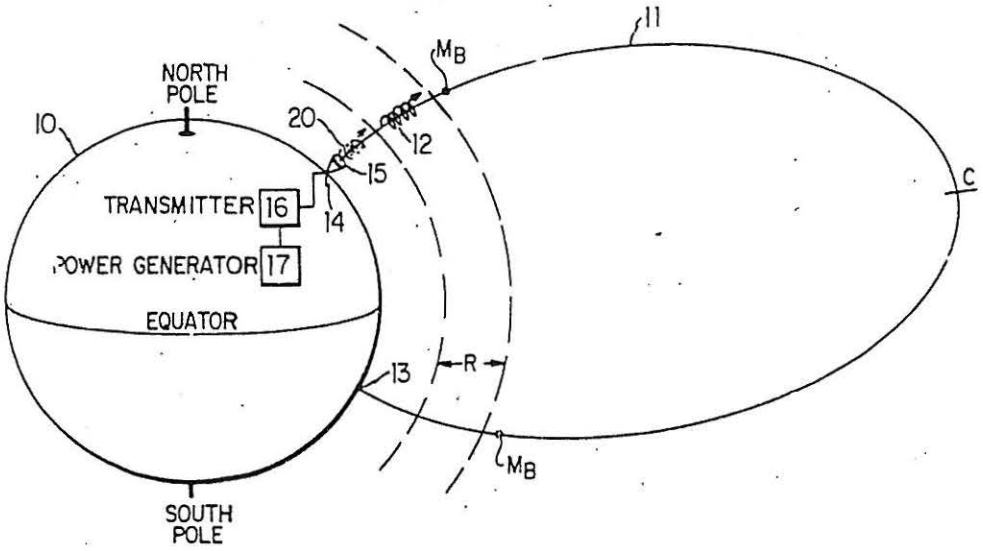


FIG. 1

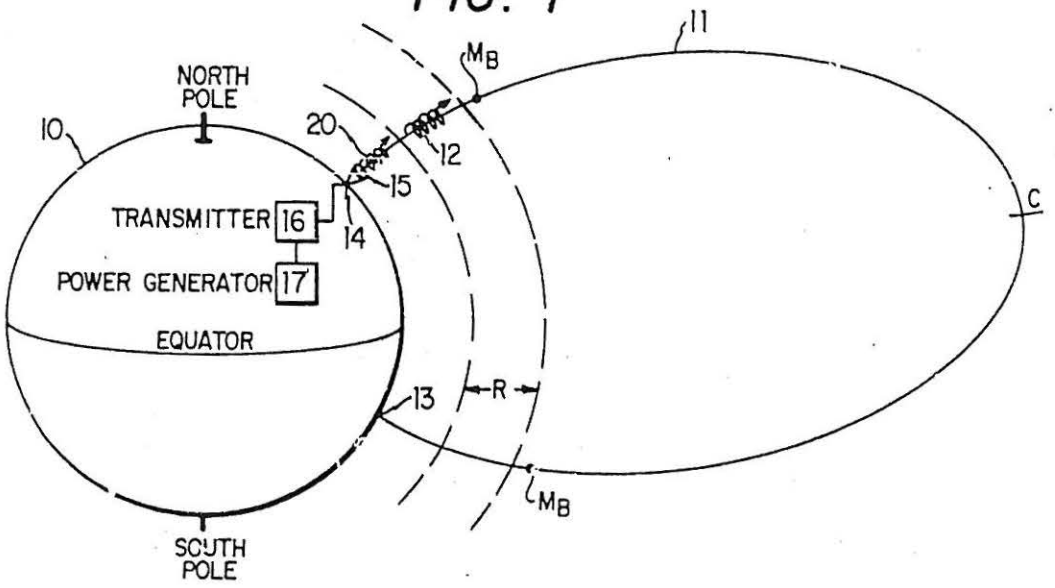

NORTH POLE
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M_B
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TRANSMITTER 16
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C
POWER GENERATOR 17
EQUATOR
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R
M_B
SOUTH POLE

FIG. 2

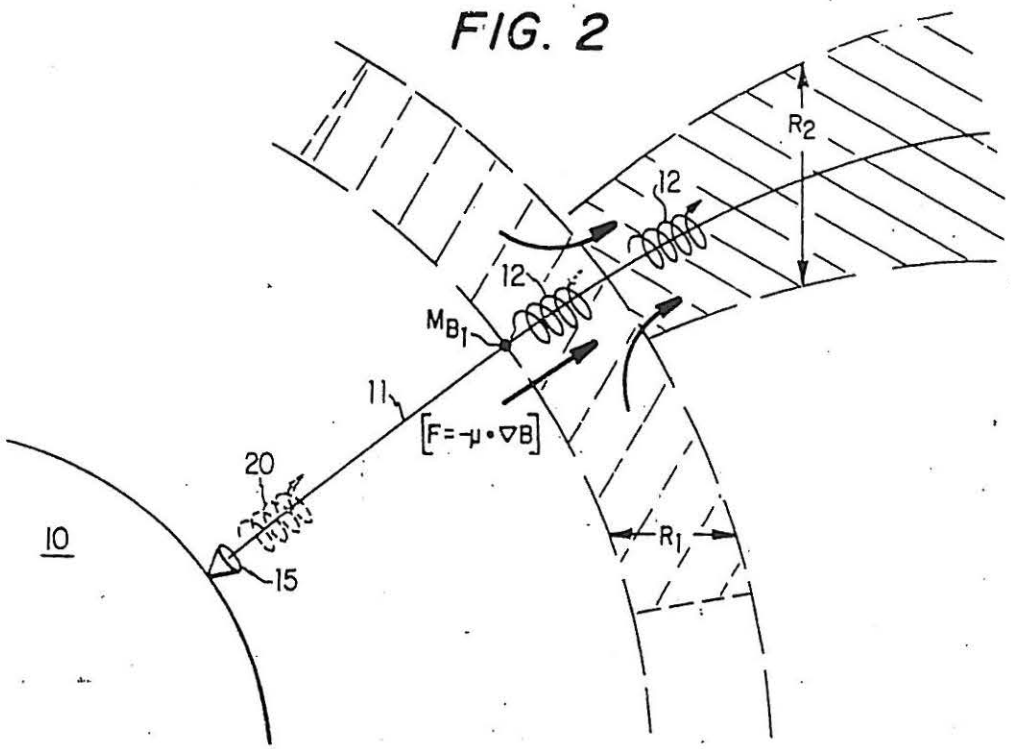
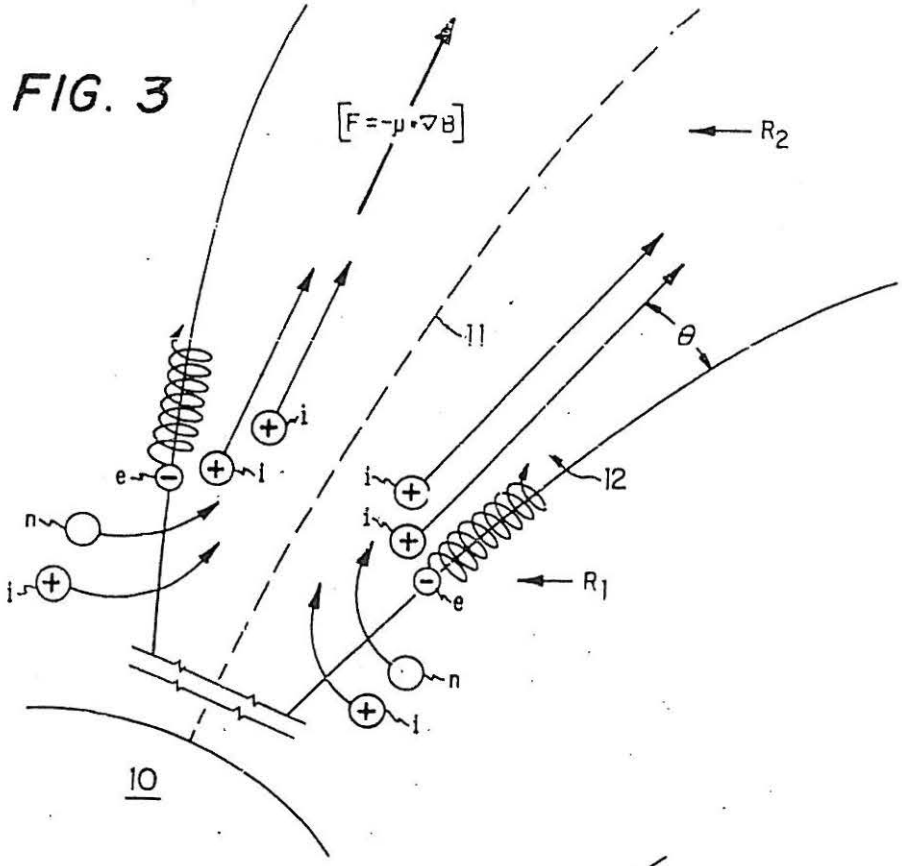

R_2
12
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M_{B1}
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$[F=-\mu \cdot \nabla B]$
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10
15
R_1

FIG. 3



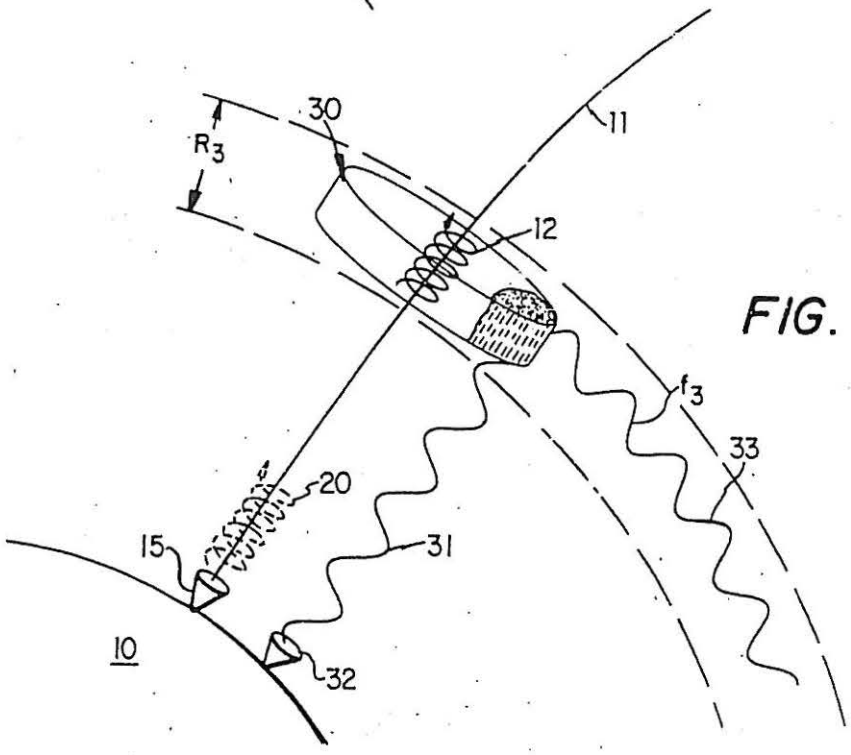


FIG. 4

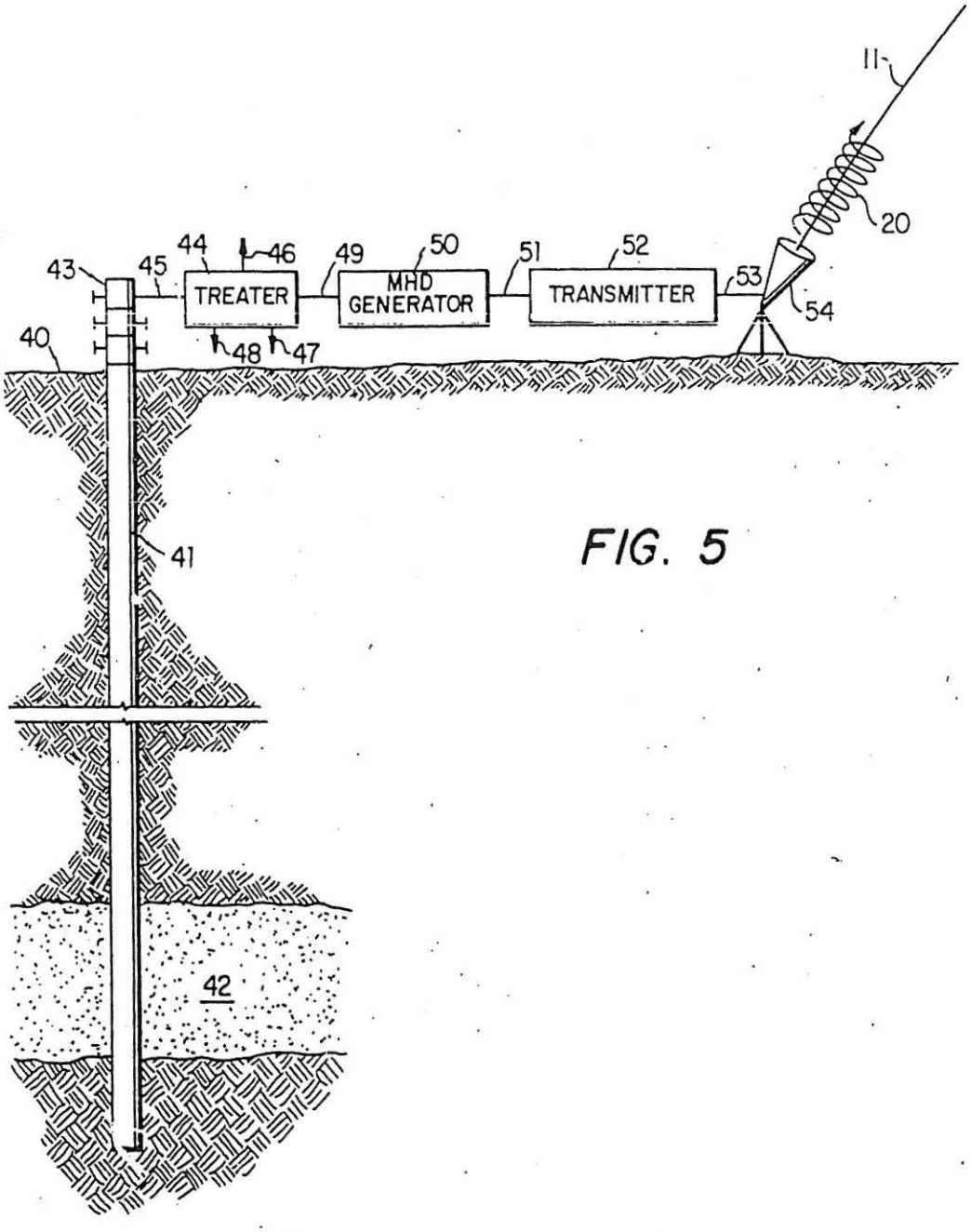

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TREATER
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MHD GENERATOR
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TRANSMITTER
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FIG. 5

METHOD AND APPARATUS FOR ALTERING A REGION IN THE EARTH'S ATMOSPHERE, IONOSPHERE, AND/OR MAGNETOSPHERE

DESCRIPTION

1. Technical Field

This invention relates to a method and apparatus for altering at least one selected region normally existing above the earth's surface and more particularly relates to a method and apparatus for altering said at least one region by initially transmitting electromagnetic radiation from the earth's surface essentially parallel to and along naturally-occurring, divergent magnetic field lines which extend from the earth's surface through the region or regions to be altered.

2. Background Art

In the late 1950's, it was discovered that naturally-occuring belts exist at high altitudes above the earth's surface, and it is now established that these belts result from charged electrons and ions becoming trapped along the magnetic lines of force (field lines) of the earth's essentially dipole magnetic field. The trapped electrons and ions are confined along the field lines between two magnetic mirrors which exist at spaced apart points along those field lines. The trapped electrons and ions move in helical paths around their particular field lines and "bounce" back and forth between the magnetic mirrors. These trapped electrons and ions can oscillate along the field lines for long periods of time.

In the past several years, substantial effort has been made to understand and explain the phenomena involved in belts of trapped electrons and ions, and to explore possible ways to control and use these phenomena for beneficial purposes. For example, in the late 1950's and early 1960's both the United States and U.S.S.R detonated a series of nuclear devices of various yields to generate large numbers of charged particles at various altitudes, e.g., 200 kilometers (km) or greater. This was done in order to establish and study artifical belts of trapped electrons and ions. These experiments established that at least some of the extraneous electrons and ions from the detonated devices did become trapped along field lines in the earth's magnetosphere to form artificial belts which were stable for prolonged periods of time. For a discussion of these experiments see "The Radiation Belt and Magnetosphere", W. N. Hess, Blaisdell Publishing Co., 1968, pps. 155 et sec.

Other proposals which have been advanced for altering existing belts of trapped electrons and ions and/or establishing similar artificial belts include injecting charged particles from a satellite carrying a payload of radioactive beta-decay material or alpha emitters; and injecting charged particles from a satellite-borne electron accelerator. Still another approach is described in U.S. Pat. No. 4,042,196 wherein a low energy ionized gas, e.g., hydrogen, is released from a synchronous orbiting satellite near the apex of a radiation belt which is naturally-occurring in the earth's magnetosphere to produce a substantial increase in energetic particle precipitation and, under certain conditions, produce a limit in the number of particles that can be stably trapped. This precipitation effect arises from an enhancement of the whistler-mode and ion-cyclotron mode interactions

that result from the ionized gas or "cold plasma" injection.

It has also been proposed to release large clouds of barium in the magnetosphere so that photoionization will increase the cold plasma density, thereby producing electron precipitation through enhanced whistler-mode interactions.

However, in all of the above-mentioned approaches, the mechanisms involved in triggering the change in the trapped particle phenomena must be actually positioned within the affected zone, e.g., the magnetosphere, before they can be actuated to effect the desired change.

The earth's ionosphere is not considered to be a "trapped" belt since there are few trapped particles therein. The term "trapped" herein refers to situations where the force of gravity on the trapped particles is balanced by magnetic forces rather than hydrostatic or collisional forces. The charged electrons and ions in the ionosphere also follow helical paths around magnetic field lines within the ionosphere but are not trapped between mirrors, as in the case of the trapped belts in the magnetosphere, since the gravitational force on the particles is balanced by collisional or hydrostatic forces.

In recent years, a number of experiments have actually been carried out to modify the ionosphere in some controlled manner to investigate the possibility of a beneficial result. For detailed discussions of these operations see the following papers: (1) Ionospheric Modification Theory; G. Meltz and F. W. Perkins; (2) The Platteville High Power Facility; Carrol et al.; (3) Arecibo Heating Experiments; W. E. Gordon and H. C. Carlson, Jr.; and (4) Ionospheric Heating by Powerful Radio Waves; Meltz et al., all published in Radio Science, Vol. 9, No. 11, November, 1974, at pages 885–888; 889–894; 1041–1047; and 1049–1063, respectively, all of which are incorporated herein by reference. In such experiments, certain regions of the ionosphere are heated to change the electron density and temperature within these regions. This is accomplished by transmitting from earth-based antennae high frequency electromagnetic radiation at a substantial angle to, not parallel to, the ionosphere's magnetic field to heat the ionospheric particles primarily by ohmic heating. The electron temperature of the ionosphere has been raised by hundreds of degrees in these experiments, and electrons with several electron volts of energy have been produced in numbers sufficient to enhance airglow. Electron concentrations have been reduced by a few percent, due to expansion of the plasma as a result of increased temperature.

In the Elmo Bumpy Torus (EBT), a controlled fusion device at the Oak Ridge National Laboratory, all heating is provided by microwaves at the electron cyclotron resonance interaction. A ring of hot electrons is formed at the earth's surface in the magnetic mirror by a combination of electron cyclotron resonance and stochastic heating. In the EBT, the ring electrons are produced with an average "temperature" of 250 kilo electron volts or kev (2.5×10^9K) and a plasma beta between 0.1 and 0.4; see, "A Theoretical Study of Electron—Cyclotron Absorption in Elmo Bumpy Torus", Batchelor and Goldfinger, Nuclear Fusion, Vol. 20, No. 4 (1980) pps. 403–418.

Electron cyclotron resonance heating has been used in experiments on the earth's surface to produce and accelerate plasmas in a diverging magnetic field. Kosmahl et al. showed that power was transferred from the electromagnetic waves and that a fully ionized plasma

was accelerated with a divergence angle of roughly 13 degrees. Optimum neutral gas density was 1.7×10^{14} per cubic centimeter; see, "Plasma Acceleration with Microwaves Near Cyclotron Resonance", Kosmahl et al., Journal of Applied Physics, Vol. 38, No. 12, Nov., 1967, pps. 4576-4582.

DISCLOSURE OF THE INVENTION

The present invention provides a method and apparatus for altering at least one selected region which normally exists above the earth's surface. The region is excited by electron cyclotron resonance heating of electrons which are already present and/or artifically created in the region to thereby increase the charged particle energy and ultimately the density of the region.

In one embodiment this is done by transmitting circularly polarized electromagnetic radiation from the earth's surface at or near the location where a naturally-occurring dipole magnetic field (force) line intersects the earth's surface. Right hand circular polarization is used in the northern hemisphere and left hand circular polarization is used in the southern hemisphere. The radiation is deliberately transmitted at the outset in a direction substantially parallel to and along a field line which extends upwardly through the region to be altered. The radiation is transmitted at a frequency which is based on the gyrofrequency of the charged particles and which, when applied to the at least one region, excites electron cyclotron resonance within the region or regions to heat and accelerate the charged particles in their respective helical paths around and along the field line. Sufficient energy is employed to cause ionization of neutral particles (molecules of oxygen, nitrogen and the like, particulates, etc.) which then become a part of the region thereby increasing the charged particle density of the region. This effect can further be enhanced by providing artificial particles, e.g., electrons, ions, etc., directly into the region to be affected from a rocket, satellite, or the like to supplement the particles in the naturally-occurring plasma. These artificial particles are also ionized by the transmitted electromagnetic radiation thereby increasing charged particle density of the resulting plasma in the region.

In another embodiment of the invention, electron cyclotron resonance heating is carried out in the selected region or regions at sufficient power levels to allow a plasma present in the region to generate a mirror force which forces the charged electrons of the altered plasma upward along the force line to an altitude which is higher than the original altitude. In this case the relevant mirror points are at the base of the altered region or regions. The charged electrons drag ions with them as well as other particles that may be present. Sufficient power, e.g., 10^{15} joules, can be applied so that the altered plasma can be trapped on the field line between mirror points and will oscillate in space for prolonged periods of time. By this embodiment, a plume of altered plasma can be established at selected locations for communication modification or other purposes.

In another embodiment, this invention is used to alter at least one selected region of plasma in the ionosphere to establish a defined layer of plasma having an increased charged particle density. Once this layer is established, and while maintaining the transmission of the main beam of circularly polarized electromagnetic radiation, the main beam is modulated and/or at least one second different, modulated electromagnetic radiation beam is transmitted from at least one separate source at a different frequency which will be absorbed in the plasma layer. The amplitude of the frequency of the main beam and/or the second beam or beams is modulated in resonance with at least one known oscillation mode in the selected region or regions to excite the known oscillation mode to propagate a known frequency wave or waves throughout the ionosphere.

BRIEF DESCRIPTION OF THE DRAWINGS

The actual construction, operation, and apparent advantages of this invention will be better understood by referring to the drawings in which like numerals identify like parts and in which:

FIG. 1 is a simplified schematical view of the earth (not to scale) with a magnetic field (force) line along which the present invention is carried out;

FIG. 2 is one embodiment within the present invention in which a selected region of plasma is raised to a higher altitude;

FIG. 3 is a simplified, idealized representation of a physical phenomenon involved in the present invention; and

FIG. 4 is a schematic view of another embodiment within the present invention.

FIG. 5 is a schematic view of an apparatus embodiment within this invention.

BEST MODES FOR CARRYING OUT THE INVENTION

The earth's magnetic field is somewhat analogous to a dipole bar magnet. As such, the earth's magnetic field contains numerous divergent field or force lines, each line intersecting the earth's surface at points on opposite sides of the Equator. The field lines which intersect the earth's surface near the poles have apexes which lie at the furthest points in the earth's magnetosphere while those closest to the Equator have apexes which reach only the lower portion of the magnetosphere.

At various altitudes above the earth's surface, e.g., in both the ionosphere and the magnetosphere, plasma is naturally present along these field lines. This plasma consists of equal numbers of positively and negatively charged particles (i.e., electrons and ions) which are guided by the field line. It is well established that a charged particle in a magnetic field gyrates about field lines, the center of gyration at any instance being called the "guiding-center" of the particle. As the gyrating particle moves along a field line in a uniform field, it will follow a helical path about its guiding center, hence linear motion, and will remain on the field line. Electrons and ions both follow helical paths around a field line but rotate in opposite directions. The frequencies at which the electrons and ions rotate about the field line are called gyromagnetic frequencies or cyclotron frequencies because they are identical with the expression for the angular frequencies of gyration of particles in a cyclotron. The cyclotron frequency of ions in a given magnetic field is less than that of electrons, in inverse proportion to their masses.

If the particles which form the plasma along the earth's field lines continued to move with a constant pitch angle, often designated "alpha", they would soon impact on the earth's surface. Pitch angle alpha is defined as the angle between the direction of the earth's magnetic field and the velocity (V) of the particle. However, in converging force fields, the pitch angle does change in such a way as to allow the particle to

turn around and avoid impact. Consider a particle moving along a field line down toward the earth. It moves into a region of increasing magnetic field strength and therefore sine alpha increases. But sine alpha can only increase to 1.0, at which point, the particle turns around and starts moving up along the field line, and alpha decreases. The point at which the particle turns around is called the mirror point, and there alpha equals ninety degrees. This process is repeated at the other end of the field line where the same magnetic field strength value B, namely Bm, exists. The particle again turns around and this is called the "conjugate point" of the original mirror point. The particle is therefore trapped and bounces between the two magnetic mirrors. The particle can continue oscillating in space in this manner for long periods of time. The actual place where a particle will mirror can be calculated from the following:

$$\sin^2 \text{alpha}_o = B_o/B_m \quad (1)$$

wherein:

alpha_o = equatorial pitch angle of particle

B_o = equatorial field strength on a particular field line

B_m = field strength at the mirror point

Recent discoveries have established that there are substantial regions of naturally trapped particles in space which are commonly called "trapped radiation belts". These belts occur at altitudes greater than about 500 km and accordingly lie in the magnetosphere and mostly above the ionosphere.

The ionosphere, while it may overlap some of the trapped-particle belts, is a region in which hydrostatic forces govern its particle distribution in the gravitational field. Particle motion within the ionosphere is governed by both hydrodynamic and electrodynamic forces. While there are few trapped particles in the ionosphere, nevertheless, plasma is present along field lines in the ionosphere. The charged particles which form this plasma move between collisions with other particles along similar helical paths around the field lines and although a particular particle may diffuse downward into the earth's lower atmosphere or lose energy and diverge from its original field line due to collisions with other particles, these charged particles are normally replaced by other available charged particles or by particles that are ionized by collision with said particle. The electron density (N_e) of the plasma will vary with the actual conditions and locations involved. Also, neutral particles, ions, and electrons are present in proximity to the field lines.

The production of enhanced ionization will also alter the distribution of atomic and molecular constituents of the atmosphere, most notably through increased atomic nitrogen concentration. The upper atmosphere is normally rich in atomic oxygen (the dominant atmospheric constituent above 200 km altitude), but atomic nitrogen is normally relatively rare. This can be expected to manifest itself in increased airglow, among other effects.

As known in plasma physics, the characteristics of a plasma can be altered by adding energy to the charged particles or by ionizing or exciting additional particles to increase the density of the plasma. One way to do this is by heating the plasma which can be accomplished in different ways, e.g., ohmic, magnetic compression, shock waves, magnetic pumping, electron cyclotron resonance, and the like.

Since electron cyclotron resonance heating is in-[illegible] in the present invention, a brief discussion of same is in order. Increasing the energy of electrons in a plasma by invoking electron cyclotron resonance heating, is based on a principle similar to that utilized to accelerate charged particles in a cyclotron. If a plasma is confined by a static axial magnetic field of strength B, the charged particles will gyrate about the lines of force with a frequency given, in hertz, as $f_g = 1.54 \times 10^3 B/A$, where: B = magnetic field strength in gauss, and A = mass number of the ion.

Suppose a time-varying field of this frequency is superimposed on the static field B confining the plasma, by passage of a radiofrequency current through a coil which is concentric with that producing the axial field, then in each half-cycle of their rotation about the field lines, the charged particles acquire energy from the oscillating electric field associated with the radio frequency. For example, if B is 10,000 gauss, the frequency of the field which is in resonance with protons in a plasma is 15.4 megahertz.

As applied to electrons, electron cyclotron resonance heating requires an oscillating field having a definite frequency determined by the strength of the confining field. The radio-frequency radiation produces time-varying fields (electric and magnetic), and the electric field accelerates the charged particle. The energized electrons share their energy with ions and neutrals by undergoing collisions with these particles, thereby effectively raising the temperature of the electrons, ions, and neutrals. The apportionment of energy among these species is determined by collision frequencies. For a more detailed understanding of the physics involved, see "Controlled Thermonuclear Reactions", Glasstone and Lovberg, D. Van Nostrand Company, Inc., Princeton, N.J., 1960 and "The Radiation Belt and Magnetosphere", Hess, Blaisdell Publishing Company, 1968, both of which are incorporated herein by reference.

Referring now to the drawings, the present invention provides a method and apparatus for altering at least one region of plasma which lies along a field line, particularly when it passes through the ionosphere and/or magnetosphere. FIG. 1 is a simplified illustration of the earth 10 and one of its dipole magnetic force or field lines 11. As will be understood, line 11 may be any one of the numerous naturally existing field lines and the actual geographical locations 13 and 14 of line 11 will be chosen based on a particular operation to be carried out. The actual locations at which field lines intersect the earth's surface is documented and is readily ascertainable by those skilled in the art.

Line 11 passes through region R which lies at an altitude above the earth's surface. A wide range of altitudes are useful given the power that can be employed by the practice of this invention. The electron cyclotron resonance heating effect can be made to act on electrons anywhere above the surface of the earth. These electrons may be already present in the atmosphere, ionosphere, and/or magnetosphere of the earth, or can be artificially generated by a variety of means such as x-ray beams, charged particle beams, lasers, the plasma sheath surrounding an object such as a missile or meteor, and the like. Further, artificial particles, e.g., electrons, ions, etc., can be injected directly into region R from an earth-launched rocket or orbiting satellite carrying, for example, a payload of radioactive beta-decay material; alpha emitters; an electron accelerator; and/or ionized gases such as hydrogen; see U.S. Pat. No. 4,042,196. The altitude can be greater than about 50 km if desired,

e.g., can be from about 50 km to about 800 km, and, accordingly may lie in either the ionosphere or the magnetosphere or both. As explained above, plasma will be present along line 11 within region R and is represented by the helical line 12. Plasma 12 is comprised of charged particles (i.e., electrons and ions) which rotate about opposing helical paths along line 11.

Antenna 15 is positioned as close as is practical to the location 14 where line 11 intersects the earth's surface. Antenna 15 may be of any known construction for high directionality, for example, a phased array, beam spread angle (θ) type. See "The MST Radar at Poker Flat, Alaska", Radio Science, Vol. 15, No. 2, Mar.-Apr. 1980, pps. 213-223, which is incorporated herein by reference. Antenna 15 is coupled to transmitter 16 which generates a beam of high frequency electromagnetic radiation at a wide range of discrete frequencies, e.g., from about 20 to about 1800 kilohertz (kHz).

Transmitter 16 is powered by power generator means 17 which is preferably comprised of one or more large, commercial electrical generators. Some embodiments of the present invention require large amounts of power, e.g., up to 10^9 to 10^{11} watts, in continuous wave or pulsed power. Generation of the needed power is within the state of the art. Although the electrical generators necessary for the practice of the invention can be powered in any known manner, for example, by nuclear reactors, hydroelectric facilities, hydrocarbon fuels, and the like, this invention, because of its very large power requirement in certain applications, is particularly adapted for use with certain types of fuel sources which naturally occur at strategic geographical locations around the earth. For example, large reserves of hydrocarbons (oil and natural gas) exist in Alaska and Canada. In northern Alaska, particularly the North Slope region, large reserves are currently readily available. Alaska and northern Canada also are ideally located geographically as to magnetic latitudes. Alaska provides easy access to magnetic field lines that are especially suited to the practice of this invention, since many field lines which extend to desirable altitudes for this invention intersect the earth in Alaska. Thus, in Alaska, there is a unique combination of large, accessible fuel sources at desirable field line intersections. Further, a particularly desirable fuel source for the generation of very large amounts of electricity is present in Alaska in abundance, this source being natural gas. The presence of very large amounts of clean-burning natural gas in Alaskan latitudes, particularly on the North Slope, and the availability of magnetohydrodynamic (MHD), gas turbine, fuel cell, electrogasdynamic (EGD) electric generators which operate very efficiently with natural gas provide an ideal power source for the unprecedented power requirements of certain of the applications of this invention. For a more detailed discussion of the various means for generating electricity from hydrocarbon fuels, see "Electrical Aspects of Combustion", Lawton and Weinberg, Clarendon Press, 1969. For example, it is possible to generate the electricity directly at the high frequency needed to drive the antenna system. To do this, typically the velocity of flow of the combustion gases (v), past magnetic field perturbation of dimension d (in the case of MHD), follow the rule:

$$v = df$$

where f is the frequency at which electricity is generated. Thus, if $v = 1.78 \times 10^6$ cm/sec and d = 1 cm then electricity would be generated at a frequency of 1.78 mHz.

Put another way, in Alaska, the right type of fuel (natural gas) is naturally present in large amounts and at just the right magnetic latitudes for the most efficient practice of this invention, a truly unique combination of circumstances. Desirable magnetic latitudes for the practice of this invention interest the earth's surface both northerly and southerly of the equator, particularly desirable latitudes being those, both northerly and southerly, which correspond in magnitude with the magnetic latitudes that encompass Alaska.

Referring now to FIG. 2 a first ambodiment is illustrated where a selected region R_1 of plasma 12 is altered by electron cyclotron resonance heating to accelerate the electrons of plasma 12, which are following helical paths along field line 11.

To accomplish this result, electromagnetic radiation is transmitted at the outset, essentially parallel to line 11 via antenna 15 as right hand circularly polarized radiation wave 20. Wave 20 has a frequency which will excite electron cyclotron resonance with plasma 12 at its initial or original altitude. This frequency will vary depending on the electron cyclotron resonance of region R_1 which, in turn, can be determined from available data based on the altitudes of region R_1, the particular field line 11 being used, the strength of the earth's magnetic field, etc. Frequencies of from about 20 to about 7200 kHz, preferably from about 20 to about 1800 kHz can be employed. Also, for any given application, there will be a threshhold (minimum power level) which is needed to produce the desired result. The minimum power level is a function of the level of plasma production and movement required, taking into consideration any loss processes that may be dominant in a particular plasma or propagation path.

As electron cyclotron resonance is established in plasma 12, energy is transferred from the electromagnetic radiation 20 into plasma 12 to heat and accelerate the electrons therein and, subsequently, ions and neutral particles. As this process continues, neutral particles which are present within R_1 are ionized and absorbed into plasma 12 and this increases the electron and ion densities of plasma 12. As the electron energy is raised to values of about 1 kilo electron volt (kev), the generated mirror force (explained below) will direct the excited plasma 12 upward along line 11 to form a plume R_2 at an altitude higher than that of R_1.

Plasma acceleration results from the force on an electron produced by a nonuniform static magnetic field ($\bar{B}$). The force, called the mirror force, is given by

$$F = -\mu \nabla B \qquad (2)$$

where μ is the electron magnetic moment and $\nabla \bar{B}$ is the gradient of the magnetic field, μ being further defined as:

$$W_\perp / B = m V_\perp^2 / 2B$$

where $W_\perp$ is the kinetic energy in the direction perpendicular to that of the magnetic field lines and B is the magnetic field strength at the line of force on which the guiding center of the particle is located. The force as represented by equation (2) is the force which is responsible for a particle obeying equation (1).

Since the magnetic field is divergent in region R_1, it can be shown that the plasma will move upwardly from the heating region as shown in FIG. 1 and further it can be shown that

$$\frac{1}{2}M_eV_{e\perp}^2(x) = \frac{1}{2}M_eV_{e\perp}^2(Y) + \frac{1}{2}M_iV_{i\parallel}^2(Y) \quad (3)$$

where the left hand side is the initial electron transverse kinetic energy; the first term on the right is the transverse electron kinetic energy at some point (Y) in the expanded field region, while the final term is the ion kinetic energy parallel to B at point (Y). This last term is what constitutes the desired ion flow. It is produced by an electrostatic field set up by electrons which are accelerated according to Equation (2) in the divergent field region and pulls ions along with them. Equation (3) ignores electron kinetic energy parallel to B because $V_{e\parallel} \approx V_{i\parallel}$, so the bulk of parallel kinetic energy resides in the ions because of their greater masses. For example, if an electromagnetic energy flux of from about 1 to about 10 watts per square centimeter is applied to region R, whose altitude is 115 km, a plasma having a density (N_e) of 10^{12} per cubic centimeter will be generated and moved upward to region R_2 which has an altitude of about 1000 km. The movement of electrons in the plasma is due to the mirror force while the ions are moved by ambipolar diffusion (which results from the electrostatic field). This effectively "lifts" a layer of plasma 12 from the ionosphere and/or magnetosphere to a higher elevation R_2. The total energy required to create a plasma with a base area of 3 square kilometers and a height of 1000 km is about 3×10^{13} joules.

FIG. 3 is an idealized representation of movement of plasma 12 upon excitation by electron cyclotron resonance within the earth's divergent force field. Electrons (e) are accelerated to velocities required to generate the necessary mirror force to cause their upward movement. At the same time neutral particles (n) which are present along line 11 in region R_1 are ionized and become part of plasma 12. As electrons (e) move upward along line 11, they drag ions (i) and neutrals (n) with them but at an angle θ of about 13 degrees to field line 11. Also, any particulates that may be present in region R_1, will be swept upwardly with the plasma. As the charged particles of plasma 12 move upward, other particles such as neutrals within or below R_1, move in to replace the upwardly moving particles. These neutrals, under some conditions, can drag with them charged particles.

For example, as a plasma moves upward, other particles at the same altitude as the plasma move horizontally into the region to replace the rising plasma and to form new plasma. The kinetic energy developed by said other particles as they move horizontally is, for example, on the same order of magnitude as the total zonal kinetic energy of stratospheric winds known to exist.

Referring again to FIG. 2, plasma 12 in region R_1 is moved upward along field line 11. The plasma 12 will then form a plume (cross-hatched area in FIG. 2) which will be relatively stable for prolonged periods of time. The exact period of time will vary widely and be determined by gravitational forces and a combination of radiative and diffusive loss terms. In the previous detailed example, the calculations were based on forming a plume by producing 0^+ energies of 2 ev/particle. About 10 ev per particle would be required to expand plasma 12 to apex point C (FIG. 1). There at least some of the particles of plasma 12 will be trapped and will oscillate between mirror points along field line 11. This oscillation will then allow additional heating of the trapped plasma 12 by stochastic heating which is associated with trapped and oscillating particles. See "A New Mechanism for Accelerating Electrons in the Outer Ionosphere" by R. A. Helliwell and T. F. Bell, Journal of Geophysical Research, Vol. 65, No. 6, June, 1960. This is preferably carried out at an altitude of at least 500 km.

The plasma of the typical example might be employed to modify or disrupt microwave transmissions of satellites. If less than total black-out of transmission is desired (e.g., scrambling by phase shifting digital signals), the density of the plasma (N_e) need only be at least about 10^6 per cubic centimeter for a plasma orginating at an altitude of from about 250 to about 400 km and accordingly less energy (i.e., electromagnetic radiation), e.g., 10^8 joules need be provided. Likewise, if the density N_e is on the order of 10^8, a properly positioned plume will provide a reflecting surface for VHF waves and can be used to enhance, interfere with, or otherwise modify communication transmissions. It can be seen from the foregoing that by appropriate application of various aspects of this invention at strategic locations and with adequate power sources, a means and method is provided to cause interference with or even total disruption of communications over a very large portion of the earth. This invention could be employed to disrupt not only land based communications, both civilian and military, but also airborne communications and sea communications (both surface and subsurface). This would have significant military implications, particularly as a barrier to or confusing factor for hostile missiles or airplanes. The belt or belts of enhanced ionization produced by the method and apparatus of this invention, particularly if set up over Northern Alaska and Canada, could be employed as an early warning device, as well as a communications disruption medium. Further, the simple ability to produce such a situation in a practical time period can by itself be a deterring force to hostile action. The ideal combination of suitable field lines intersecting the earth's surface at the point where substantial fuel sources are available for generation of very large quantitities of electromagnetic power, such as the North Slope of Alaska, provides the wherewithal to accomplish the foregoing in a practical time period, e.g., strategic requirements could necessitate achieving the desired altered regions in time periods of two minutes or less and this is achievable with this invention, especially when the combination of natural gas and magnetohydrodynamic, gas turbine, fuel cell and/or EGD electric generators are employed at the point where the useful field lines intersect the earth's surface. One feature of this invention which satisfies a basic requirement of a weapon system, i.e., continuous checking of operability, is that small amounts of power can be generated for operability checking purposes. Further, in the exploitation of this invention, since the main electromagnetic beam which generates the enhanced ionized belt of this invention can be modulated itself and/or one or more additional electromagnetic radiation waves can be impinged on the ionized region formed by this invention as will be described in greater detail herein after with respect to FIG. 4, a substantial amount of randomly modulated signals of very large power magnitude can be generated in a highly nonlinear mode. This can cause confusion of or interference with or even complete disruption of guidance systems employed by

even the most sophisticated of airplanes and missiles. The ability to employ and transmit over very wide areas of the earth a plurality of electromagnetic waves of varying frequencies and to change same at will in a random manner, provides a unique ability to interfere with all modes of communications, land, sea, and/or air, at the same time. Because of the unique juxtaposition of usable fuel source at the point where desirable field lines intersect the earth's surface, such wide ranging and complete communication interference can be achieved in a reasonably short period of time. Because of the mirroring phenomenon discussed hereinabove, it can also be prolonged for substantial time periods so that it would not be a mere transient effect that could simply be waited out by an opposing force. Thus, this invention provides the ability to put unprecedented amounts of power in the earth's atmosphere at strategic locations and to maintain the power injection level, particularly if random pulsing is employed, in a manner far more precise and better controlled than heretofore accomplished by the prior art, particularly by the detonation of nuclear devices of various yeilds at various altitudes. Where the prior art approaches yielded merely transitory effects, the unique combination of fuel and desirable field lines at the point where the fuel occurs allows the establishment of, compared to prior art approaches, precisely controlled and long-lasting effects which cannot, practically speaking, simply be waited out. Further, by knowing the frequencies of the various electromagnetic beams employed in the practice of this invention, it is possible not only to interfere with third party communications but to take advantage of one or more such beams to carry out a communications network even though the rest of the world's communications are disrupted. Put another way, what is used to disrupt another's communications can be employed by one knowledgeable of this invention as a communications network at the same time. In addition, once one's own communication network is established, the far-reaching extent of the effects of this invention could be employed to pick up communication signals of other for intelligence purposes. Thus, it can be seen that the disrupting effects achievable by this invention can be employed to benefit by the party who is practicing this invention since knowledge of the various electromagnetic waves being employed and how they will vary in frequency and magnitude can be used to an advantage for positive communication and eavesdropping purposes at the same time. However, this invention is not limited to locations where the fuel source naturally exists or where desirable field lines naturally intersect the earth's surface. For example, fuel, particularly hydrocarbon fuel, can be transported by pipeline and the like to the location where the invention is to be practiced.

FIG. 4 illustrates another embodiment wherein a selected region of plasma R_3which lies within the earth's ionosphere is altered to increase the density thereof whereby a relatively stable layer 30 of relatively dense plasma is maintained within region R_3. Electromagnetic radiation is transmitted at the outset essentially parallel to field line 11 via antenna 15 as a right hand circularly polarized wave and at a frequency (e.g., 1.78 megahertz when the magnetic field at the desired altitude is 0.66 gauss) capable of exciting electron cyclotron resonance in plasma 12 at the particular altitude of plasma 12. This causes heating of the particles (electrons, ions, neutrals, and particulates) and ionization of the uncharged particles adjacent line 11, all of which are absorbed into plasma 12 to increase the density thereof. The power transmitted, e.g., 2×10^6 watts for up to 2 minutes heating time, is less than that required to generate the mirror force F required to move plasma 12 upward as in the previous embodiment.

While continuing to transmit electromagnetic radiation 20 from antenna 15, a second electromagnetic radiation beam 31, which is at a defined frequency different from the radiation from antenna 15, is transmitted from one or more second sources via antenna 32 into layer 30 and is absorbed into a portion of layer 30 (cross-hatched area in FIG. 4). The electromagnetic radiation wave from antenna 32 is amplitude modulated to match a known mode of oscillation f_3 in layer 30. This creates a resonance in layer 30 which excites a new plasma wave 33 which also has a frequency of f_3 and which then propogates through the ionosphere. Wave 33 can be used to improve or disrupt communications or both depending on what is desired in a particular application. Of course, more than one new wave 33 can be generated and the various new waves can be modulated at will and in a highly nonlinear fashion.

FIG. 5 shows apparatus useful in this invention, particularly when those applications of this invention are employed which require extremely large amounts of power. In FIG. 5 there is shown the earth's surface 40 with a well 41 extending downwardly thereinto until it penetrates hydrocarbon producing reservoir 42. Hydrocarbon reservoir 42 produces natural gas alone or in combination with crude oil. Hydrocarbons are produced from reservoir 42 through well 41 and wellhead 43 to a treating system 44 by way of pipe 45. In treater 44, desirable liquids such as crude oil and gas condensates are separated and recovered by way of pipe 46 while undesirable gases and liquids such as water, H_2S, and the like are separated by way of pipe 47. Desirable gases such as carbon dioxide are separated by way of pipe 48, and the remaining natural gas stream is removed from treater 44 by way of pipe 49 for storage in conventional tankage means (not shown) for future use and/or use in an electrical generator such as a magnetohydrodynamic, gas turbine, fuel cell or EGD generator 50. Any desired number and combination of different types of electric generators can be employed in the practice of this invention. The natural gas is burned in generator 50 to produce substantial quantities of electricity which is then stored and/or passed by way of wire 51 to a transmitter 52 which generates the electromagnetic radiation to be used in the method of this invention. The electromagnetic radiation is then passed by way of wire 53 to antenna 54 which is located at or near the end of field line 11. Antenna 54 sends circularly polarized radiation wave 20 upwards along field line 11 to carry out the various methods of this invention as described hereinabove.

Of course, the fuel source need not be used in its naturally-occurring state but could first be converted to another second energy source form such as hydrogen, hydrazine and the like, and electricity then generated from said second energy source form.

It can be seen from the foregoing that when desirable field line 11 intersects earth's surface 40 at or near a large naturally-occurring hydrocarbon source 42, exceedingly large amounts of power can be very efficiently produced and transmitted in the direction of field lines. This is particularly so when the fuel source is natural gas and magnetohydrodynamic generators are employed. Further, this can all be accomplished in a

relatively small physical area when there is the unique coincidence of fuel source 42 and desirable field line 11. Of course, only one set of equipment is shown in FIG. 5 for sake of simplicity. For a large hydrocarbon reservoir 42, a plurality of wells 41 can be employed to feed one or more storage means and/or treaters and as large a number of generators 55 as needed to power one or more transmitters 52 and one or more antennas 54. Since all of the apparatus 44 through 54 can be employed and used essentially at the sight where naturally-occurring fuel source 42 is located, all the necessary electromagnetic radiation 20 is generated essentially at the same location as fuel source 42. This provides for a maximum amount of usable electromagnetic radiation 20 since there are no significant storage or transportation losses to be incurred. In other words, the apparatus is brought to the sight of the fuel source where desirable field line 11 intersects the earth's surface 40 on or near the geographical location of fuel source 42, fuel source 42 being at a desirable magnetic latitude for the practice of this invention, for example, Alaska.

The generation of electricity by motion of a conducting fluid through a magnetic field, i.e., magnetohydrodynamics (MHD), provides a method of electric power generation without moving mechanical parts and when the conducting fluid is a plasma formed by combustion of a fuel such as natural gas, an idealized combination of apparatus is realized since the very clean-burning natural gas forms the conducting plasma in an efficient manner and the thus formed plasma, when passed through a magnetic field, generates electricity in a very efficient manner. Thus, the use of fuel source 42 to generate a plasma by combustion thereof for the generation of electricity essentially at the site of occurrence of the fuel source is unique and ideal when high power levels are required and desirable field lines 11 intersect the earth's surface 40 at or near the site of fuel source 42. A particular advantage for MHD generators is that they can be made to generate large amounts of power with a small volume, light weight device. For example, a 1000 megawatt MHD generator can be construed using superconducting magnets to weigh roughly 42,000 pounds and can be readily air lifted.

This invention has a phenomenal variety of possible ramifications and potential future developments. As alluded to earlier, missile or aircraft destruction, deflection, or confusion could result, particularly when relativistic particles are employed. Also, large regions of the atmosphere could be lifted to an unexpectedly high altitude so that missiles encounter unexpected and unplanned drag forces with resultant destruction or deflection of same. Weather modification is possible by, for example, altering upper atmosphere wind patterns or altering solar absorption patterns by constructing one or more plumes of atmospheric particles which will act as a lens or focusing device. Also as alluded to earlier, molecular modifications of the atmosphere can take place so that positive environmental effects can be achieved. Besides actually changing the molecular composition of an atmospheric region, a particular molecule or molecules can be chosen for increased presence. For example, ozone, nitrogen, etc. concentrations in the atmosphere could be artificially increased. Similarly, environmental enhancement could be achieved by causing the breakup of various chemical entities such as carbon dioxide, carbon monoxide, nitrous oxides, and the like. Transportation of entities can also be realized when advantage is taken of the drag effects caused by regions of the atmosphere moving up along diverging field lines. Small micron sized particles can be then transported, and, under certain circumstances and with the availability of sufficient energy, larger particles or objects could be similarly affected. Particles with desired characteristics such as tackiness, reflectivity, absorptivity, etc., can be transported for specific purposes or effects. For example, a plume of tacky particles could be established to increase the drag on a missile or satellite passing therethrough. Even plumes of plasma having substantially less charged particle density than described above will produce drag effects on missiles which will affect a lightweight (dummy) missile in a manner substantially different than a heavy (live) missile and this affect can be used to distinguish between the two types of missiles. A moving plume could also serve as a means for supplying a space station or for focusing vast amount of sunlight on selected portions of the earth. Surveys of global scope could also be realized because the earth's natural magnetic field could be significantly altered in a controlled manner by plasma beta effects resulting in, for example, improved magnetotelluric surveys. Electromagnetic pulse defenses are also possible. The earth's magnetic field could be decreased or disrupted at appropriate altitudes to modify or eliminate the magnetic field in high Compton electron generation (e.g., from high altitude nuclear bursts) regions. High intensity, well controlled electrical fields can be provided in selected locations for various purposes. For example, the plasma sheath surrounding a missile or satellite could be used as a trigger for activating such a high intensity field to destroy the missile or satellite. Further, irregularities can be created in the ionosphere which will interfere with the normal operation of various types of radar, e.g., synthetic aperture radar. The present invention can also be used to create artificial belts of trapped particles which in turn can be studied to determine the stability of such parties. Still further, plumes in accordance with the present invention can be formed to simulate and/or perform the same functions as performed by the detonation of a "heave" type nuclear device without actually having to detonate such a device. Thus it can be seen that the ramifications are numerous, far-reaching, and exceedingly varied in usefulness.

I claim:

1. A method for altering at least one region normally existing above the earth's surface with electromagnetic radiation using naturally-occurring and diverging magnetic field lines of the earth comprising transmitting first electromagnetic radiation at a frequency between 20 and 7200 kHz from the earth's surface, said transmitting being conducted essentially at the outset of transmission substantially parallel to and along at least one of said field lines, adjusting the frequency of said first radiation to a value which will excite electron cyclotron resonance at an initial elevation at least 50 km above the earth's surface, whereby in the region in which said electron cyclotron resonance takes place heating, further ionization, and movement of both charged and neutral particles is effected, said cyclotron resonance excitation of said region is continued until the electron concentration of said region reaches a value of at least 10^6 per cubic centimeter and has an ion energy of at least 2 ev.

2. The method of claim 1 including the step of providing artificial particles in said at least one region which are excited by said electron cyclotron resonance

3. The method of claim 2 wherein said artificial particles are provided by injecting same into said at least one region from an orbiting satellite.

4. The method of claim 1 wherein said threshold excitation of electron cyclotron resonance is about 1 watt per cubic centimeter and is sufficient to cause movement of a plasma region along said diverging magnetic field lines to an altitude higher than the altitude at which said excitation was initiated.

5. The method of claim 4 wherein said rising plasma region pulls with it a substantial portion of neutral particles of the atmosphere which exist in or near said plasma region.

6. The method of claim 1 wherein there is provided at least one separate source of second electromagnetic radiation, said second radiation having at least one frequency different from said first radiation, impinging said at least one second radiation on said region while said region is undergoing electron cyclotron resonance excitation caused by said first radiation.

7. The method of claim 6 wherein said second radiation has a frequency which is absorbed by said region.

8. The method of claim 6 wherein said region is plasma in the ionosphere and said second radiation excites plasma waves within said ionosphere.

9. The method of claim 8 wherein said electron concentration reaches a value of at least 10^{12} per cubic centimeter.

10. The method of claim 8 wherein said excitation of electron cyclotron resonance is initially carried out within the ionosphere and is continued for a time sufficient to allow said region to rise above said ionosphere.

11. The method of claim 1 wherein said excitation of electron cyclotron resonance is carried out above about 500 kilometers and for a time of from 0.1 to 1200 seconds such that multiple heating of said plasma region is achieved by means of stochastic heating in the magnetosphere.

12. The method of claim 1 wherein said first electromagnetic radiation is right hand circularly polarized in the northern hemisphere and left hand circularly polarized in the southern hemisphere.

13. The method of claim 1 wherein said electromagnetic radiation is generated at the site of a naturally-occurring hydrocarbon fuel source, said fuel source being located in at least one of northerly or southerly magnetic latitudes.

14. The method of claim 13 wherein said fuel source is natural gas and electricity for generating said electromagnetic radiation is obtained by burning said natural gas in at least one of magnetohydrodynamic, gas turbine, fuel cell, and EGD electric generators located at the site where said natural gas naturally occurs in the earth.

15. The method of claim 14 wherein said site of natural gas is within the magnetic latitudes that encompass Alaska.

* * * * *

FIG. 1

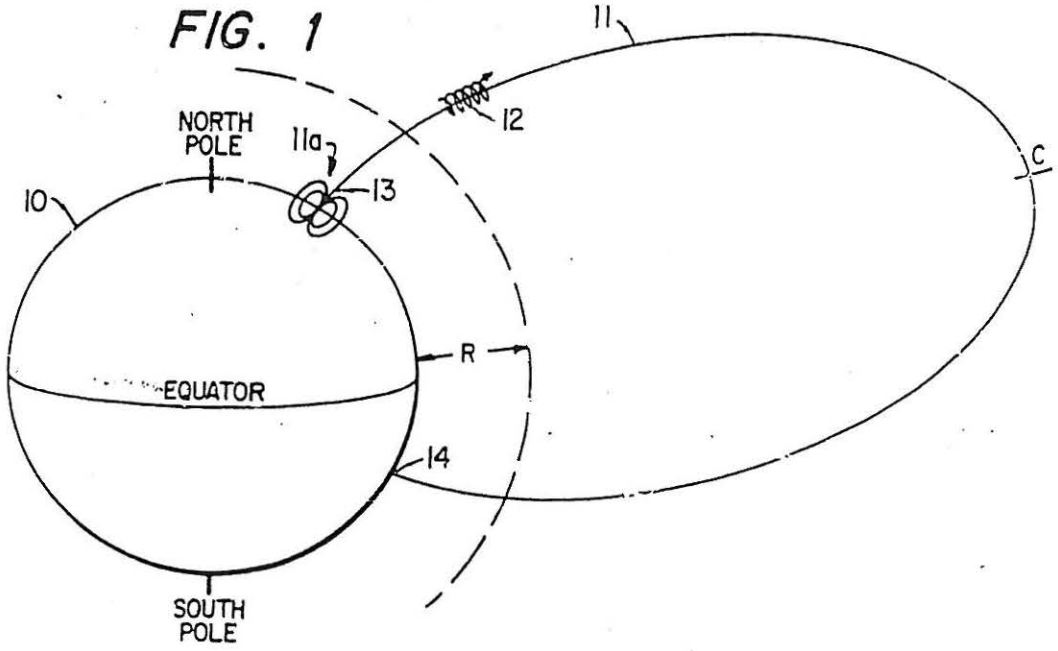

11
12
NORTH POLE
11a
13
C
10
R
EQUATOR
14
SOUTH POLE

FIG. 2

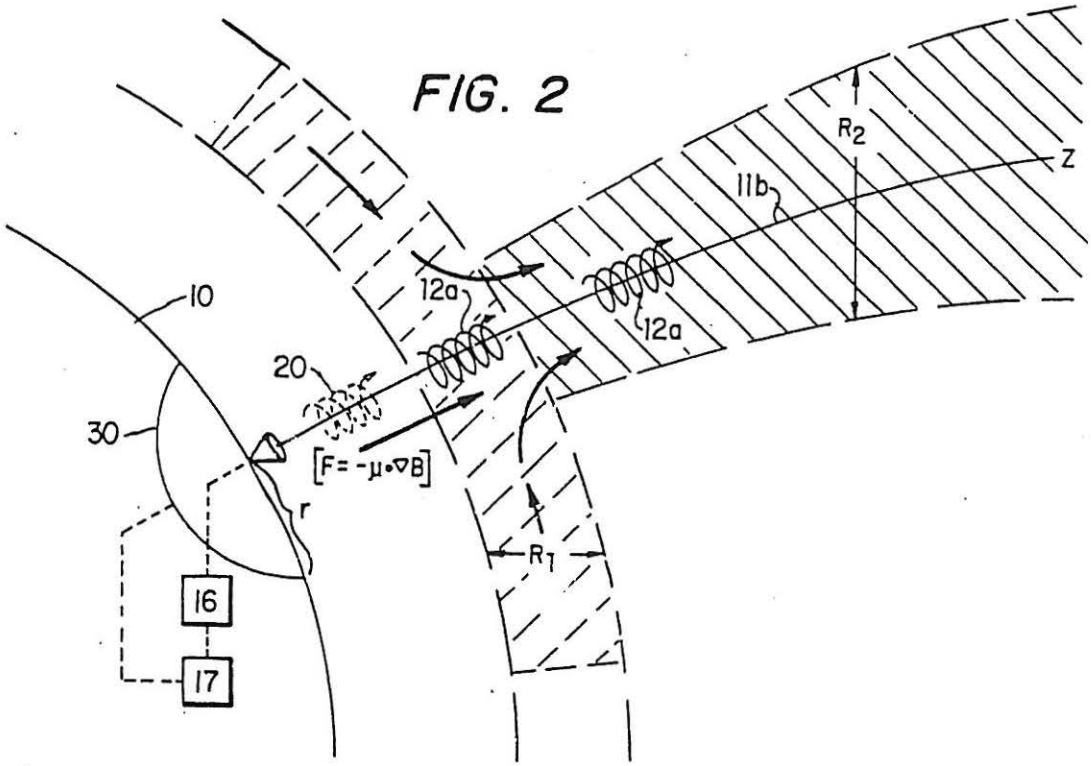

R2
Z
11b
10
12a
12a
20
30
[F= -μ•∇B]
r
R1
16
17

FIG. 3

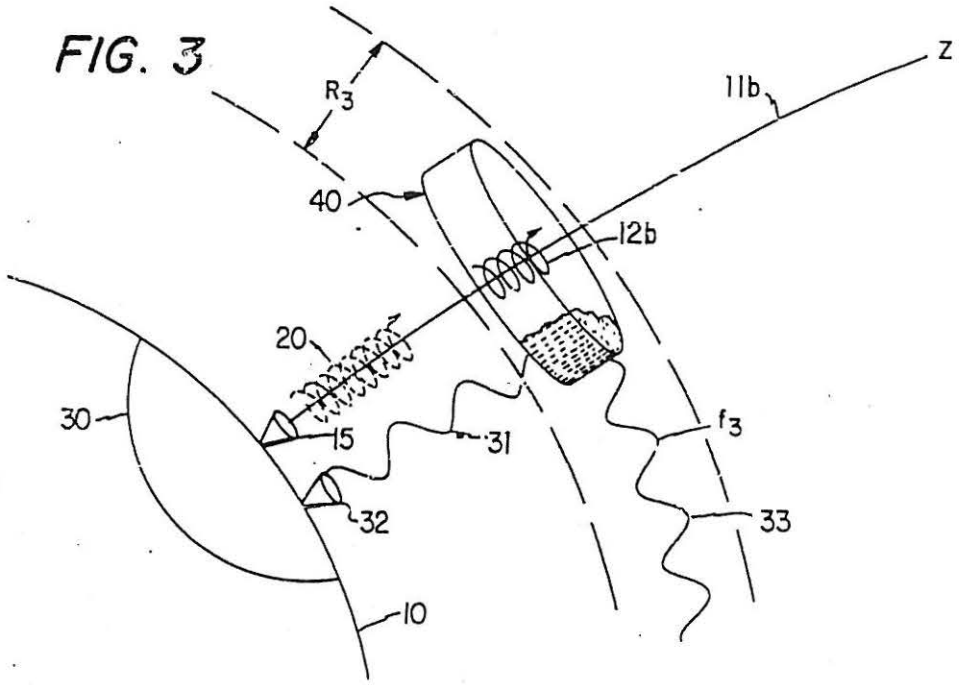
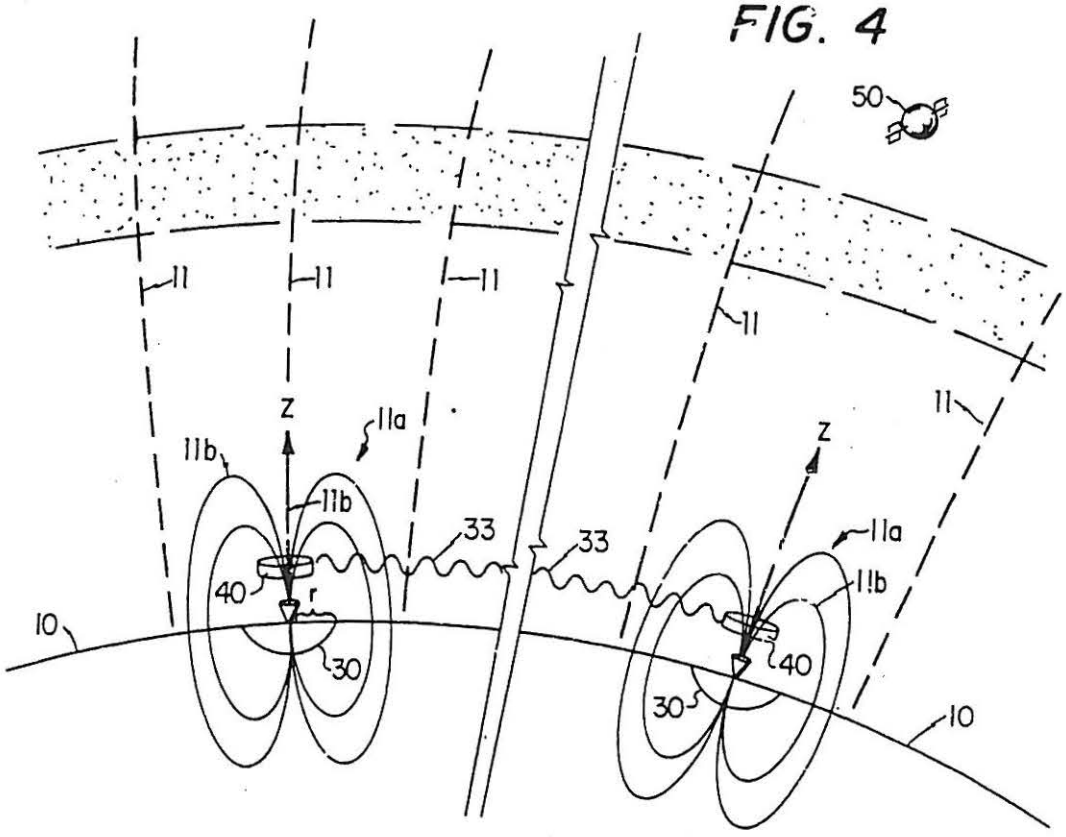

R3
Z
11b
40
12b
20
30
15
31
f3
32
33
10

FIG. 4


50
11
11
11
11
11
Z
11a
11b
11b
33
33
40
r
10
30
Z
11a
11b
40
30
10

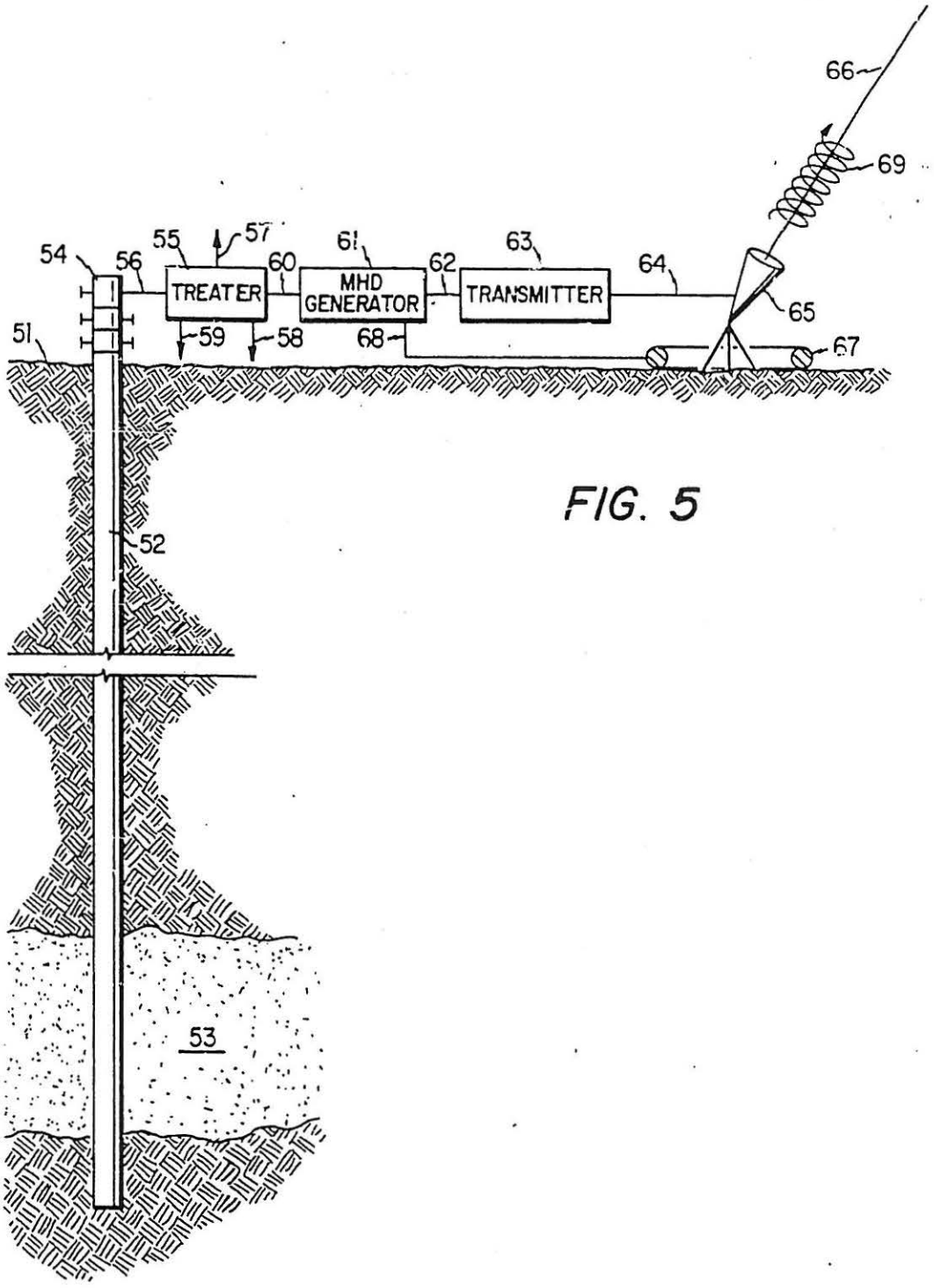

66
69
54
56
55
57
60
61
62
63
64
TREATER
MHD GENERATOR
TRANSMITTER
65
51
59
58
68
67
52
53

FIG. 5

METHOD AND APPARATUS FOR CREATING AN ARTIFICIAL ELECTRON CYCLOTRON HEATING REGION OF PLASMA

DESCRIPTION

1. Technical Field

This invention relates to a method and apparatus for creating an artificial electric cyclotron resonance heating region of plasma and more particularly relates to creating artificial magnetic field lines from the earth's surface and thus altering at least one region of plasma normally existing along said artificial lines at a selected altitude above the earth's surface.

2. Background Art

The earth's magnetic field is somewhat analogous to a dipole bar magnet. As such, the earth's magnetic field contains numerous divergent field or force lines, each line having ends which intersect the earth's surface at points on opposite sides of the Equator. The field lines which intersect the earth's surface near the poles have apexes which lie at the furthest points in the earth's magnetosphere while those closest to the Equator have apexes which reach only the lower portion of the magnetosphere.

Above the earth's surface, plasma is naturally present along these field lines. This plasma consists of equal numbers of positively and negatively charges particles (i.e., electrons and ions) which are guided by the field line. It is well established that a charged particle in a magnetic field gyrates about field lines, the center of gyration at any instance being called the "guiding center" of the particle. As the gyrating particle moves along a field line in a uniform field, it will follow a helical path about its guiding center, hence linear motion, and will remain on the field line. Electrons and ions both follow helical paths around a field line but rotate in opposite directions. The frequencies at which the electrons and ions rotate about the field line are called gyromagnetic frequencies or cyclotron frequencies because they are identical with the expression for the angular frequencies of gyration of particles in a cyclotron. The cyclotron frequency of ions in a given magnetic field is less than that of electrons, in inverse proportion to their masses.

While this plasma is present at lower altitudes, e.g. below 50 kilometers, the collision rate of the electrons in the plasma becomes much greater than the cyclotron frequency of the electrons at that altitude so an electron normally experiences one or more collisions with other electrons, ions, or particles before it can complete one path around its field line. These collisions cause the electrons to continuously change course preventing the electrons from following their normal helical pathes around the field line.

At higher altitudes, the cyclotron frequency of the electrons exceed the collision rate between electrons so particular electrons may continue to follow defined helical pathes around a particular field line for prolonged periods, especially if the electrons are at a sufficient altitude and energy level to become trapped on the field line between mirror points there thereon. When the flow of electrons is relatively coherent or constant for at least a complete helical path about a field line, energy may be inputted from the earth along the field line to add energy to the electrons to substantially alter the plasma of which the electrons form a part thereof.

energy is transmitted to substantially alter a region of plasma, see copending U.S. Patent Application Ser. Nos. 690,333 and 690,354, both, filed Jan. 10, 1985.

In the above-mentioned applications, energy is added to the plasma by transmitting electromagnetic radiation to establish electron cyclotron resonance heating in a region of plasma which lies at an altitude where the cyclotron frequency is greater than the collision rate of the electrons in the plasma. Increasing the energy of electrons by electron cyclotron resonance heating, is based on a principle similar to that involved in accelerating charged particles in a cyclotron. That is, by passage of a radiofrequency current through a coil which is concentric with that producing the axial field, then in each half-cycle of their rotation about the field lines, the charged particles, e.g. electrons, acquire energy from the oscillating electric field associated with the radio frequency.

The use of electron cyclotron resonance heating to add energy to the electrons of a plasma has heretofore been restricted to regions of plasma which lie at altitudes where the cyclotron frequency exceeds the collision rate of the electrons, (e.g. ionosphere and higher). However, since many benefits (e.g. long distance communications, weather modification, etc.) may arise from being able to alter plasma regions at lower altitudes a need exists for being able to excite electron cyclotron resonant heating in regions of plasma at lower altitudes where the collision rate of the electrons is originally greater that the cyclotron frequency of the electrons.

DISCLOSURE OF THE INVENTION

The present invention provides a method and apparatus for creating an artificial electron cyclotron heating region of plasma that lies above the earth's surface at altitudes (e.g. below 50 kilometers) where the collision rate of the electrons in the plasma is orginally greater than the cyclotron frequency of the electrons. First, artificial magnetic lines of force are established from the earth's surface into the region in which the operation is to be carried out.

To establish the artificial magnetic field lines, a loop of cable is positioned at the earth's surface so that the center of the loop will be colinear with the desired artificial field lines. An electrical current of sufficient amperage is passed through the cable which inherently generates a dipole field, with the central field line thereof extending outward from the plane of the loop. The artificial magnetic field is designed so that the field strength B at the altitude of the region of plasma to be altered is sufficient to increase the cyclotron frequency of the electrons in the plasma so that it will exceed the collision rate of the electrons. When this occurs, the plasma is now in condition to be excited by electron cyclotron resonance heating to thereby increase the charged particle energy. This is done by transmitting circularly polarized electromagnetic radiation from the earth's surface at or near one end of a artificial magnetic field line where it intersects the earth's surface. Right hand circular polarization is used in the northern hemisphere and left hand circular polarization is used in the southern hemisphere. The radiation is deliberately transmitted at the outset in a direction substantially parallel to and along the artificial field line which extends upwardly through the region of plasma to be altered. The radiation is transmitted at a frequency

the charged particles and which, when applied to the plasma is said at least one region, excites electron cyclotron resonance within the plasma to heat and accelerate the charged particles in their respective helical paths around and along the field line. Sufficient energy may be employed to cause ionization of neutral particles (molecules of oxygen, nitrogen and the like, particulates, etc.) which then become a part of the plasma thereby increasing the charged particle density of the plasma.

In one embodiment of the invention, electron cyclotron resonance heating is carried out in the selected region at sufficient power levels to allow the plasma to generate a mirror force which forces the charged electrons of the altered plasma upward along the force line to an altitude which is higher than the original altitude. As the plasma moves upward, other particles from the atmosphere at the same altitude as the selected region move horizontally into the region to replace the rising plasma and to form new plasma. The kinetic energy developed by said other particles as they move horizontally is on the same order of magnitude of as the total zonal kinetic energy of stratospheric winds known to exist at altitudes equal to the region being altered. Since there is evidence that these stratospheric winds may be linked to certain weather patterns on earth, the present method may be used to affect similar patterns.

In another embodiment, the present method is used to alter at least one selected region of plasma in the stratosphere to establish a defined layer of plasma having an increased charged particle density. Once this layer is established and while maintaining the transmission of the main beam of circularly polarized electromagnetic radiation, the main beam is modulated and/or at least one second different, modulated electromagnetic radiation beam is transmitted from at least one separate source at a different frequency which will be absorbed in the plasma layer. The amplitude of the frequency of the main beam and/or the second beam or beams is modulated in resonance with at least one known oscillation mode in the selected region or regions to excite the known oscillation mode to propagate a known frequency wave or waves throughout the stratosphere which may be used in communications.

BRIEF DESCRIPTION OF THE DRAWINGS

The actual construction, operation, and apparent advantages of the present invention will be better understood by referring to the drawings in which like numerals identify like parts and in which:

FIG. 1 is a simplified schematical view of the earth (not to scale) with a naturally occurring magnetic field (force) line having an artificial magnetic field thereon in accordance with the present invention;

FIG. 2 is one embodiment within the present invention in which a selected region of plasma is raised to a higher altitude to thereby induce horizontal flow in said region;

FIG. 3 is a schematic view of another embodiment within the present invention; and

FIG. 4 is a schematic view of still a further embodiment within the present invention; and

FIG. 5 is a schematic vien of apparatus within the present invention.

BEST MODES FOR CARRYING OUT THE INVENTION

Referring now more particularly to the drawings, FIG. 1 is a simplified illustration of the earth 10 and one of its naturally occuring dipole magnetic field lines 11.

As will be understood, line 11 may be any one of the numerous naturally existing field lines and the actual geopraphical location, at which the ends 13 and 14 of line 11 intersect the earth's surface is documented and is readily ascertainable by those skilled in the art. Plasma 12 is naturally present along these field lines. This plasma consists of equal numbers of positively and negatively charged particles (i.e., electrons and ions) which are guided by the field line 11.

It is well established that a charged particle in a magnetic field will gryrate about field lines unless it collides with another particle. As the gryrating particle moves along a field line in a uniform field, it will follow a helical path about its guiding center, hence linear motion, and will remain on the field line. Electrons and ions both follow helical paths around a field line but rotate in opposite directions. The frequencies at which the electrons and ions rotate about the field line are called gyromagnetic frequencies or cyclotron frequencies because they are identical with the expression for the angular frequencies of gyration of particles in a cyclotron. The cyclotron frequency of ions in a given magnetic field is less than that of electrons, in inverse proportion to their masses.

As shown in FIG.1, the electrons in plasma 12 which lie at or above an altitude, e g. at least about 66 kilometers, where the cyclotron frequency of the electrons are greater than the collision rate of the electrons will, in fact, follow helical paths around line 11. However, in region R, which includes those altitudes (e.g. less than about 50 kilometers) at which the collision rate of electrons exceed the cyclotron frequency of the electrons, individual electrons (not shown) will collide with other particles before they complete a helical path around line 11 and will be deflected therefrom. The charged particles which form plasma in region R move between collisions with other particles along similar helical paths around the field lines and although a particular particle may diffuse downward into the earth's lower atmosphere or lose energy and diverge from its original field line due to collisions with other particles, these charged particles are normally replaced by other available charged particles or by particles that are ionized by collision with said particle. The electron density (N_e) of the plasma will vary with the actual conditions and locations involved. Also, neutral particles, ions, and electrons are present in proximity to the field lines.

As known in plasma physics, the characteristics of a plasma can be altered by adding energy to the charged particles or by ionizing or exciting additional particles to increase the density of the plasma. One way to do this is by heating the plasma which can be accomplished in different ways, e.g., ohmic, magnetic compression, shock waves, magnetic pumping, electron cyclotron resonance, and the like.

Since electron cyclotron resonance heating is involved in the present invention, a brief discussion of same is in order. Increasing the energy of electrons in a plasma by invoking electron cyclotron resonance heating, is based on a principle similar to that utilized to accelerate charged particles in a cyclotron. If a plasma is confined by a static axial magnetic field of strength B,

the charged particles will gyrate about the lines of force with a frequency given, in hertz, as $f_g = 1.54 \times 10^3$ B/A, where: B = magnetic field strength in gauss, and A = mass number of the ion.

Suppose a time-varying field of this frequency is superimposed on the static field B confining the plasma, by passage of a radiofrequency current through a coil which is concentric with that producing the axial field, then in each half-cycle of their rotation about the field lines, the charged particles acquire energy from the oscillating electric field associated with the radio frequency. For example, if B is 10,000 gauss, the frequency of the field which is in resonance with protons in a plasma is 15.4 megahertz.

As applied to electrons, electron cyclotron resonance heating requires an oscillating field having a definite frequency determined by the strength of the confining field. The radiofrequency radiation produces time-varying fields (electric and magnetic), and the electric field accelerates the charged particle. The energized electrons share their energy with ions and neutrals by undergoing collisions with these particles, thereby effectively raising the temperature of the electrons, ions, and neutrals. The apportionment of energy among these species is determined by collision frequencies. For a more detailed understanding of the physics involved, see "Controlled Thermonuclear Reactions", Glasstone and Lovberg, D. Van Nostrand Company, Inc., Princeton, N.J., 1960 and "The Radiation Belt and Magnetosphere", Hess, Blaisdell Publishing Company, 1968.

However, before electron cyclotron resonant heating can be excited in the plasma of region R, the cyclotron frequency of the electrons therein has to be increased until it is greater than the collision rate of the electrons. This is accomplished in the present invention by establishing an artificial dipole magnet field **11***a* within region R which has sufficient field strength B to increase the cyclotron frequency of electrons **12***a* (FIG. 3) at the attitude of interest until it exceeds the collosion rate of the electrons at that attitude.

A preferred means to establish artificial magnetic field **11***a* is shown in FIGS. 2, 3 and 4. A circular loop **30** (only half is shown) of an electrically-conductive cable is positioned at the earth's surface **10** at a location at which the artificial magnetic line **11***b* is to intersect the earth's surface. Loop **30** maybe positioned on an incline, e.g. mountain so that artificial line **11***b* will be projected outwardly at an angle respective to horizontal at the earth's surface and also with respect to naturally-occurring magnetic line **11**. Electrical current at high amperage is supplied to loop **30** and flowed therethrough which then establishes artificial line **11***b* which extends outward from the center of loop **30**.

The following is a typical example of an artificial magnetic line **11***b* which is to established in accordance with the present invention. A location is selected in the State of Alaska in an area commonly referred to as the North Slope. Plasma in region R at an altitude of about 35 kilometers is to be altered. The field strength B which is typical at this altitude along the naturally occurring field line in this area is approximately 0.62 gauss. This strength B at this altitude is such that the collision rate of the electrons (FIG. 3) is greater than their cyclotron frequency and must be increased (for example, by 10 fold) to insure the cyclotron frequency becomes greater than the collision rate. The following known relationship for magnetic induction on the center line of a circular turn where the distance in the Z direction (i.e. altitude of R.) is equal to the radius r of loop **30** can be used to properly dimension loop **30** and determine the necessary amperage:

$$B = \frac{\mu_o I r^2}{2(2r^2)}$$

wherein:

B = Desired field strength at 100 kilometer = 1.1×10^{-3} webers/sq. meters

$\mu = 4\pi \times 10^{-7}$

I = current in amps

r = radius of loop in meter

Substituting known values (i.e. radius of loop 30 is approximately equal to the altitude or 100 kilometers in this example), the above equation is solved to establish that 5×10^8 amperes of current will need to be flowed through loop **30** having a radius of 100 kilometers to produce an artificial field line **11***b* which has a field strength of 1.1×10^{-3} webers/sq. meters. To transmit this current will require a superconducting cable having about a one-meter diameter and is within the art of superconducting power transmission, see Electrical Characteristics of a Superconducting Cable; Chowder, CRYOGENICS; April, 1982.

Once artificial magnetic line **11***b* is established, the cyclotron frequency of the charged particles in plasma **12***a* in region R_1 will now be greater than the collision rate which permits the charged particles of plasma **12***a* to follow helical paths around line **11***b* so that it can now be altered further by exciting electron cyclotron resonance heating in plasma **12***a* to add energy to the charged particles or by exciting or ionizing additional particles to increase the density of the plasma.

To do this, antenna **15** is positioned as close as is practical to the center of loop **30**. Antenna **15** may be of any known construction for high directionality, for example, a phased array, beam spread angle (O) type. See "The MST Radar at Poker Flat, Alaska", Radio Science, Vol. 15, No. 2, March-April 1980, pps. 213-223, which is incorporated herein by reference. Antenna **15** is coupled to transmitter **16** which generates a beam of high frequency electromagnetic radiation at a wide range of discrete frequencies, e.g., from about 10 kilohertz to about 30 gigahertz.

Transmitter **16** as well as loop **30** is powered by power generator means **17** which is preferably comprised of one or more large, commercial electrical generators. Some embodiments of the present invention require large amounts of power, e.g., up to 10^9 to 10^{11} watts, in continuous wave or pulsed power. Generation of the needed power is within the state of the art. Although the electrical generators necessary for the practice of the invention can be powered in any known manner, for example, by nuclear reactors, hydroelectric facilities, hydrocarbon fuels, and the like, this invention, because of its very large power requirement in certain applications, is particularly adapted for use with certain types of fuel sources which naturally occur at strategic geographical locations around the earth. For example, large reserves of hydrocarbons (oil and natural gas) exist in Alaska and Canada. In northern Alaska, particularly the North Slope region, large reserves are currently readily available. Alaska and northern Canada also are ideally located geographically as to magnetic latitudes. Thus, in Alaska, there is a unique combination of large, accessible fuel sources at desirable field line

intersections. Further, a particularly desirable fuel source for the generation of very large amounts of electricity is present in Alaska in abundance, this source being natural gas. The presence of very large amounts of clean-burning natural gas in Alaskan latitudes, particularly on the North Slope, and the availability of magnetohydrodynamic electric generators which operate very efficiently with natural gas provides an ideal power source for the unprecedented power requirements of certain of the applications of this invention.

Referring now to FIG. 3, a first embodiment of how plasma **12***a* is altered is illustrated where a selected region R_1 of plasma **12***a* is altered by electron cyclotron resonance heating to accelerate the electrons of plasma **12**, which are following helical paths along artificial field line **11***b* which has been established as explained above.

To accomplish this result, electromagnetic radiation is transmitted at the outset, essentially parallel to artificial field line **11***b* via antenna **15** as right hand circularly polarized radiation wave **20**. Wave **20** has a frequency which will excite electron cyclotron resonance with plasma **12** at its initial or original altitude. This frequency will vary depending on the electron cyclotron resonance of region R_1 which, in turn, can be determined from available data based on the altitude of region R_1, the strength B of the on artficial magnetic field **11***b* at said altitude, etc. Frequencies of from about 10 kilohertz to about 30 gigahertz can be employed. Also, for any given application, there will be a threshhold (minimum power level) which is needed to produce the desired result. The minimum power level is a function of the level of plasma production and movement required, taking into consideration any loss processes that may be dominant in a particular plasma or propagation path.

As electron cyclotron resonance is established in plasma **12***a*, energy is transferred from the electromagnetic radiation **20** into plasma **12***a* to heat and accelerate the electrons therein and, subsequently, ions and neutral particles. As this process continues, neutral particles which are present within R_1 are ionized and absorbed into plasma **12***a* and this increases the electron and ion densities of plasma **12***a*. As the electron energy is raised to values of about 1 kilo electron volt (kev), the generated mirror force (explained below) will direct the excited plasma **12** upward along line **11***a* in the form of plume R_2 at an altitude higher than that of R_1.

Plasma acceleration results from the force on an electron produced by a nonuniform static magnetic field (B). The force, called the mirror force, is given by

$$\bar{F} = -\mu \nabla \bar{B}$$

where μ is the electron magnetic moment and $\nabla\bar{B}$ is the gradient of the magnetic field, being further defined as:

$$W\perp/B = mV\perp^2/2B$$

where $W\perp$ is the kinetic energy in the direction perpendicular to that of the magnetic field lines and B is the magnetic field strength at the line of force on which the guiding center of the particle is located. The force as represented by equation (2) is the force which is responsible for a particle obeying equation (1).

Since the magnetic field is divergent in region R_1, it can be shown that the plasma will move upwardly from the heating region as shown in FIG. 1 and further it can be shown that

$$\tfrac{1}{2}M_e V_e\perp^2(x) = \tfrac{1}{2}M_e V_e\perp^2(Y) + \tfrac{1}{2}M_i V_{iII}^2(Y) \quad (3)$$

where the left hand side is the initial electron transverse kinetic energy; the first term on the right is the transverse electron kinetic energy at some point (Y) in the expanded field region, while the final term is the ion kinetic energy parallel to B at point (Y). This last term is what constitutes the desired ion flow. It is produced by an electrostatic field set up by electrons which are accelerated according to Equation (2) in the divergent field region and pulls ions along with them. Equation (3) ignores electron kinetic energy parallel to B because $V_{eII} \ll V_{iII}$, so the bulk of parallel kinetic energy resides in the ions because of their greater masses. For example, if an electromagnetic energy flux of from about 1 to about 10 watts per square centimeter is applied to region R, whose altitude is 100 km, a plasma having a density (N_e) 10^{13} per cubic centimeter will be generated and moved upward with a verticle component of kinetic energy equal to 10^7 ergs/cm^2. The movement of electrons in the plasma is due to the mirror force while the ions are moved by ambipolar diffusion. This effectively "lifts" a layer of plasma **12***a* from region R_1 to a higher elevation R_2.

The electrons are accelerated to velocities required to generate the necessary mirror force to cause their upward movement. At the same time neutral particles which are present along line **11***a* in region R_1 are ionized and become part of plasma **12***a*. As electrons move upward along line **11***a*, they drag ions and neutrals with them. Also, any particulates that may be present in region R_1, will be swept upwardly with the plasma. As the charged particles of plasma **12***a* move upward, other particles such as neutrals within R_1, move horizontally in to replace the upwardly moving particles. As plasma **12***a* is being moved upward with a very high kinetic energy in the vertical direction (e.g. 10^7 ergs/cm^2), the flow of the atmosphere particles to replace the rising plasma will have comparable kinetic energy in the horizontal direction. The horizontal kinetic energy so generated will be of the same order of magnitude as the total zonal kinetic energy of naturally-occurring stratospheric wind at altitudes of 22 to 32 kilometer; see "The Energetics of the Stratosphere during the Winter Warmings of 1970/71 and 1974/75;" E. Klinker, COSPAR SPACE RESEARCH, Vol. XVii, Pergamon Press, 1977. Since there is evidence that wind currents in the stratosphere appear to be linked to certain weather patterns on earth, such winds can be produced with the present invention at selected locations and altitudes which can be used in establishing such weather patterns.

FIG. 3 illustrates another embodiment wherein a selected region R of plasma **12***a* at a low altitude to increase the density thereof whereby a relatively stable layer **40** of relatively dense plasma is maintained within region R_3. First artificial magnetic line **11***b* is established as disclosed above. Electromagnetic radiation is then transmitted at the outset essentially parallel to field **11***b* via antenna **15** as a right hand circularly polarized wave and at a frequency (e.g., 178 megahertz when the magnetic field at the desired altitude is 1.1×10^{-3} webers/sq. meter) capable of exciting electron cyclotron resonance in plasma **12***b* in Region R_3. This causes heating of the particles (electrons, ions, neutrals, and partic-

ulates) and ionization of the uncharged particles adjacent line 11*b*, all of which are absorbed into plasma 12*b* to increase the density thereof. The power transmitted, e.g., 10^{-5} watts $-cm^2$ for up to 10 minutes heating time, is less than that required to generate the mirror force F required to move plasma 12*b* upward as in the previous embodiment.

While continuing to transmit electromagnetic radiation 20 from antenna 15, a second electromagnetic radiation beam 31, which is at a defined frequency different from the radiation from antenna 15, is transmitted from one or more second sources via antenna 32 into layer 40 and is absorbed into a portion of layer 40 (cross-hatched area in FIG. 4). The electromagnetic radiation wave from antenna 32 is amplitude modulated to match a known mode of oscillation f_3 in layer 30. This creates a resonance in layer 30 which excites a new plasma wave 33 which also has a frequency of f_3 and which then propogates through region R. Wave 33 can be used to improve or disrupt communications or both depending on what is desired in a particular application. Of course, more than one new wave 33 can be generated and the various new waves can be modulated at will and in a highly nonlinear fashion.

FIG. 4 illustrates still a further embodiment of the present invention wherein more than one artificial magnetic field 11*a* is established at points spaced from each other on the earth's surface 10. Each magnetic field 11*a* is established as described in connection with FIG. 3 above and a stable layer 40 of relatively dense plasma is maintained on magnetic field line 11*b* of each field at approximately the same attitudes. A plasma wave 33 is excited as described above and propogates between the spaced layers 40 and can be used to enhance communications between the points at which the artificial magnetic fields are located and at points therebetween. That is, a communication signal can be transmitted onto wave 33 at any point along wave 33 and will be carried thereby throughout the wavepath. This signal can be retrieved by receivers (not shown) spaced at points on the earth's surface below the wavepath. This modification is particularly useful in establishing communications between points on the earth when communications via orbiting satellite 50 may become blocked by a dense layer D of high intensity, trapped charged particles at higher altitudes. Layers D of such particles have been shown to be possible as a result of the denotation of nuclear devices at such altitudes or the like.

FIG. 5 shows apparatus useful in this invention. In FIG. 5 there is shown the earth's surface 51 with a well 52 extending downwardly thereinto until it penetrates hydrocarbon producing reservoir 53. Hydrocarbon reservoir 53 produces natural gas alone or in combination with crude oil. Hydrocarbons are produced from reservoir 53 through well 52 and wellhead 54 to a treating system 55 by way of pipe 56. In treater 55 desirable liquids such as crude oil and gas condensates are separated and recovered by way of pipe 57 while undesirable gases and liquids such as water, H_2S, and the like are separated by way of pipe 58. Desirable gases such as carbon dioxide are separated by way of pipe 59, and the remaining natural gas stream is removed from treater 55 by way of pipe 60 for storage in conventional tankage means (not shown) for future use and/or use in an electrical generator 61 such as a magnetohydrodynamic, gas turbine, fuel cell or EGD generator. Any desired number and combination of different types of electric generators can be employed in the practice of this invention.

The natural gas is burned in generator 61 to produce substantial quantities of electricity which is then stored and/or passed by way of wire 62 to a transmitter 63 which generates the electromagnetic radiation to be used in the method of this invention. The electromagnetic radiation is then passed by way of wire 64 to antenna 65 which is located at or near the end of artificial field line 66. Artificial field line 66 is generated by electromagnetic coil 67 which is powered by way of wire 68 from generator 61. Antenna 65 sends circularly polarized radiation wave 69 upwards along artificial field line 66 to carry out the various methods of this invention as described hereinabove.

The fuel source need not be used in its naturally-occurring state but could first be converted to another second energy source form such as hydrogen, hydrazine and the like, and electricity then generated from said second energy source form.

It can be seen from the foregoing that an artificial magnetic field line can be established at or near a large naturally-occurring hydrocarbon source and exceedingly large amounts of power can be very efficiently produced and used to generate magnetic field lines and to transmit radiation along said field lines. This is particularly so when the fuel source is natural gas and magnetohydrodynamic generators are employed.

Only one set of equipment is shown in FIG. 5 for sake of simplicity. For a large hydrocarbon reservoir 53, a plurality of wells 52 can be employed to feed one or more storage means and/or treaters 55 and as large a number of generators 61 as needed to power one or more transmitters 63, antennas 65, and coils 67. Since all of the apparatus 55 through 68 can be employed and used essentially at the site where naturally-occurring fuel source 53 is located, all the necessary artificial field lines 66 and electromagnetic radiation 69 is generated essentially at the same location as fuel source 53. This provides for a maximum amount of usable energy since there are no significant storage or transportation losses to be incurred.

It can be seen from the foregoing that this invention can be applied to any artificial magnetic field or fields wherever located and whether uniform or nonuniform in nature. This invention can be employed in any region of the atmosphere or space where an artificial magnetic field or fields can be generated after which the electron cyclotron resonance heating is carried out as described herein. Thus, this invention can be practiced with a very small localized uniform or irregular magnetic field or with a much larger artificial magnetic field such as those approaching the size and uniformity of naturally-occuring magnetic ficids. Although it may not be practical in some cases to employ an artificial magnetic field approaching the size of the earth's natural magnetic field, this invention can be employed to augment, complement or otherwise utilize or improve upon such naturally-occurring fields.

Accordingly, this invention could be employed in a method for altering at least one region normally existing above the earth's surface with electromagnetic radiation using artificially generated and diverging magnetic field lines comprising generating the artificial field line or lines, transmitting first electromagnetic radiation from the earth's surface, said transmitting being conducted substantially parallel to and along at least one of said artificial field lines, adjusting the frequency of this

first radiation to a value which will excite electron cyclotron resonance at an initial elevation above the earth's surface, whereby in the region in which the electron cyclotron resonance takes place, heating, further ionization, and movement of both charged and neutral particles is effected. In this process, artificial particles can be added to the region which is excited by the electron cyclotron resonance in any manner such as from a rocket or an orbiting satellite. In this method, sufficient electromagnetic radiation can be transmitted so that an altered plasma in the region is trapped on the artificial field line or lines between mirror points and oscillates back and forth therebetween. If the electron cyclotron resonance excited region is energized sufficiently to cause a rising plasma region, this rising region can pull with it a substantial portion of neutral particles which exist in or near the plasma region. In this method, the electron cyclotron excitation of the region can be continued until the electron concentration of the region reaches a value of at least 10^6 per cubic centimeter.

The method of this invention can also be employed for altering at least one selected region normally existing above the earth's surface by employing electromagnetic radiation along at least one artificially generated magnetic field line to excite electron cyclotron resonance in the region and wherein the electromagnetic radiation is generated at the site of a naturally-occurring hydrocarbon fuel source, said fuel source being located in at least one of northerly or southerly magnetic latitudes. In this method, the fuel source can be a hydrocarbon such as natural gas and electricity for generating the electromagnetic radiation is obtained by burning the hydrocarbon fuel in at least one of magnetohydrodynamic, gas turbine, fuel cell, and EGD electric generators located at the site where the hydrocarbon fuel source naturally occurs in the earth. The hydrocarbon fuel source can be located anywhere in the world such as within the natural magnetic latitutdes that encompass Alaska.

This invention also encompasses apparatus for altering at least one region normally existing above the earth's surface with electromagnetic radiation comprising a combination of a naturally-occurring fuel source, means for making the fuel source available for use, means for exploiting the fuel source to generate electricity, means for converting the generated electricity into electromagnetic radiation of a desired frequency, means for generating at least one artificial magnetic field line, and means for transmitting the electromagnetic radiation along the artificial magnetic field line. The apparatus can be employed so that the artificially generated magnetic field line intersects the earth's surface at or near the naturally-occurring fuel source. The naturally-occurring fuel source could be produced from the earth, treated for the removal of undesirable fluids and burned to generate electricity essentially at the iste where the fuel source is produced from the earth.

This invention can also be employed with apparatus for generating electromagnetic radiation in very large amounts for propogation along artificially generated magnetic field lines which comprises providing a source of combustible fuel, means for burning the fuel essentially at its location of natural occurence to form a plasma, means for employing the plasma to generate electricity, means for converting electricity into the desired electromagnetic radiation, and means for generating the required artificial magnetic field line or lines.

In addition, the method of this invention can be practiced so that the first electromagnetic radiation is modulated to excite additional plasma waves within the plasma region while the plasma region is undergoing electron cyclotron resonance excitation. The method can also be employed for exploiting a naturally-occurring underground fuel source by converting the fuel source to electricity at the site where the fuel source occurs, converting the electricity to at least one electromagnetic radiation wave of known frequency, generating at least one artificial magnetic field line, transmitting the at least one electromagnetic radiation wave into the earth's atmosphere along the artificial magnetic field line to an elevation where electron cyclotron resonance takes place at the frequency of the at least one electromagnetic radiation wave. Further, the frequency of the at least one electromagnetic radiation wave can be varied as desired, both linearly and nonlinearly.

Reasonable variations and modifications are possible within the scope of this disclosure without departing from the spirit and scope of this invention.

What is claimed is:

1. A method of creating an artificial electron cyclotron resonance heating region of plasma at about 50 km above the earth's surface in which the collision rate of the electrons in said plasma is greater than the cyclotron frequency of said electrons, said method comprising:

establishing a first artificial magnetic field having a plurality of artificial field lines which extend from the surface of the earth through said region of plasma by

positioning a circular loop of an electrical conductive cable at the surface of the earth so that the center of said loop will be colinear with the said artificial magnetic field lines;

passing an electric current through said loop to establish said artificial magnetic field having a magnetic field strength of about 10 fold greater than the field strength naturally occurring in said region; and

transmitting first circularly polarized electromagnetic radiation having a frequency from 10 kilohertz to 30 gigahertz from the earth's surface, said transmitting being conducted essentially at the outset of transmission substantially parallel to and along said field lines of said artificial magnetic field, adjusting the frequency of said first radiation to a value which will excite electron cyclotron resonance at an initial altitude of about 50 km above the earth's surface, whereby in the region in which said electron cyclotron resonance takes place heating, further ionization, and movement of both charged and neutral particles is effected.

2. The method of claim 1 wherein said excitation of electron cyclotron resonance is continued to cause movement of said plasma region along said artificial magnetic field lines upward to an altitude which is higher than the altitude at which said excitation was initiated.

3. The method of claim 2 wherein said rising plasma region pulls with it a substantial portion of neutral particles of the atmosphere which exist in or near said plasma region.

4. The method of claim 1 wherein there is provided at least one separate source of second electromagnetic radiation, said second radiation having at least one frequency different from said first radiation, impinging said at least one second radiation on said plasma region

while said plasma region is undergoing electron cyclotron resonance excitation caused by said first radiation.

5. The method of claim 4 wherein said second radiation has a frequency which is absorbed by said plasma region.

6. The method of claim 1 wherein said first electromagnetic radiation is right hand circularly polarized in the northern hemisphere and left hand circularly polarized in the southern hemisphere.

7. The method of claim 4 wherein said loop is positioned at an angle with respect to the normal horizontal plane at the earth's surface whereby said artificial magnetic force lines will extend outwardly from the earth's surface at an angle with respect to a normally occurring earth's magnetic field line.

8. The method of claim 7 wherein the radius of said loop is approximately equal to the altitude of said region.

9. The method of claim 8 wherein said region is at an altitude of about 35 kilometers.

10. The method of claim 9 wherein said cable comprises a 1 meter diameter, superconductive cable positioned in a circular loop which, in turn, has a radius of 35 kilometers and wherein said amperage is substantially about 5×10^8 amperes.

11. The method of claim 5 including:

establishing a second artificial field at a point on the earth's surface at a point spaced from said first artificial magnetic field;

establishing a second plasma region along the artificial field lines of said second artificial magnetic field at an altitude substantially the same as the altitude of said plasma region of said first magnetic field; and

propogating said plasma waves between said first and second plasma regions.

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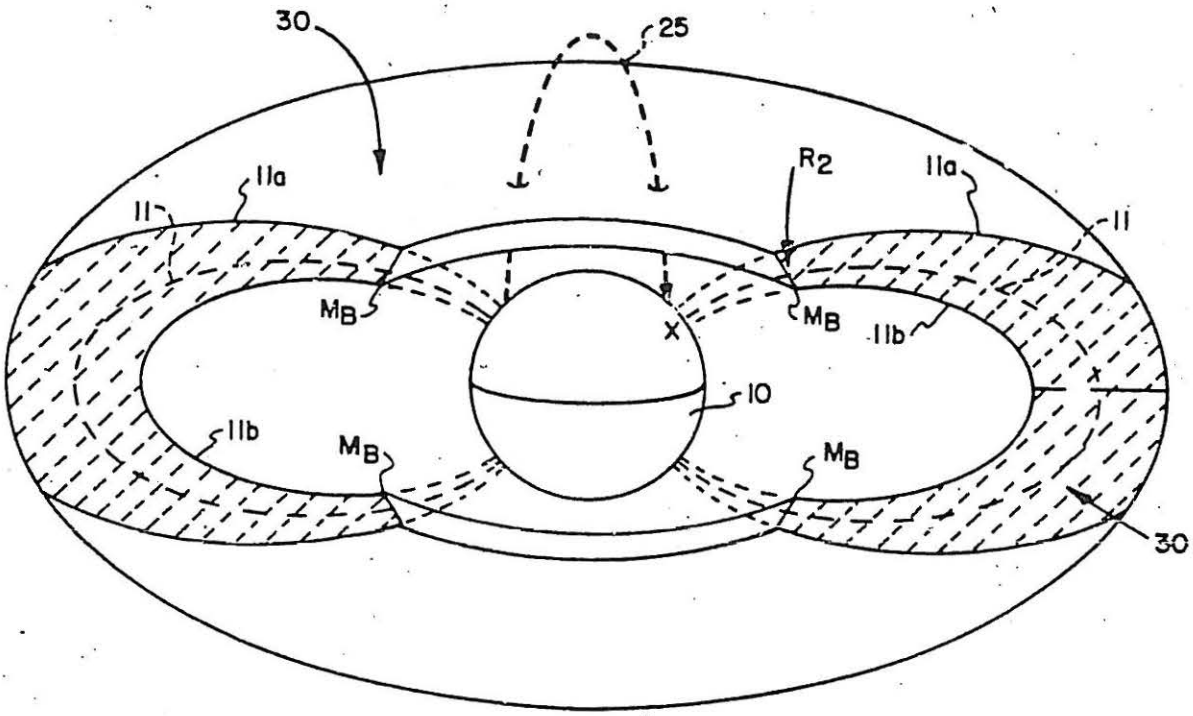


FIG. 3

United States Patent [19]

Eastlund

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[45] **Date of Patent: Aug. 13, 1991**

[54] **METHOD FOR PRODUCING A SHELL OF RELATIVISTIC PARTICLES AT AN ALTITUDE ABOVE THE EARTHS SURFACE**

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[21] Appl. No.: **690,354**

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[51] **Int. Cl.**[5] **F41B 15/00**

[52] **U.S. Cl.** **89/1.11**; 376/100; 376/123

[58] **Field of Search** 376/100, 123; 89/1.11; 361/231; 342/352

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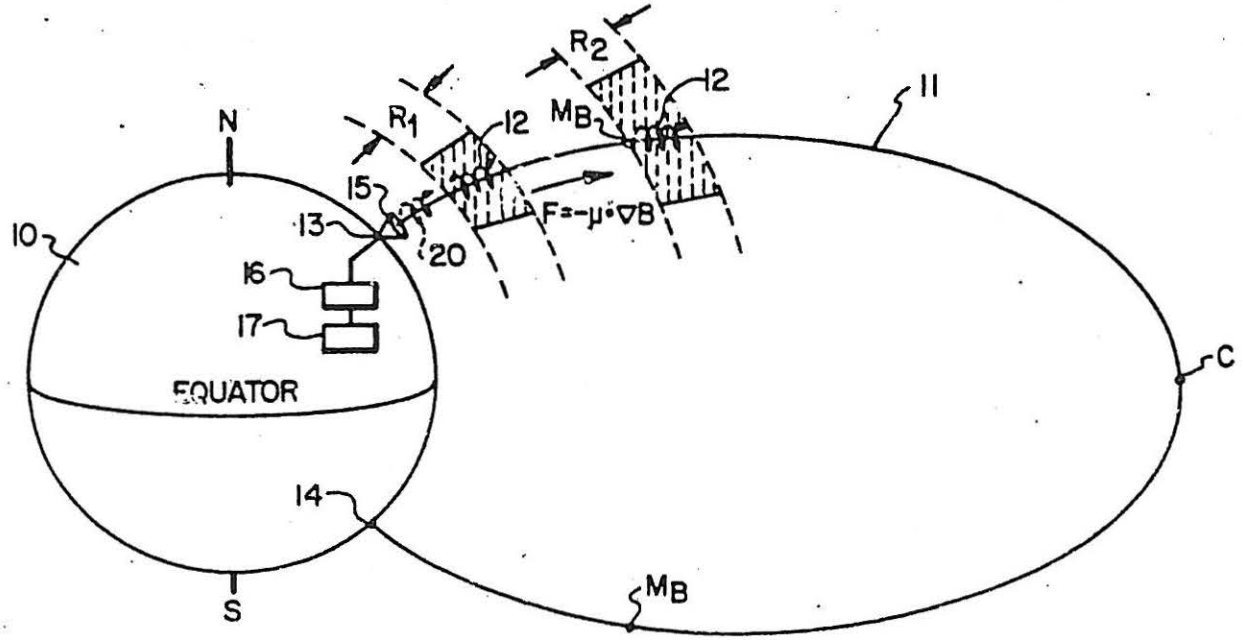
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[57] **ABSTRACT**

A method for establishing a region of a high density, high energy plasma at an altitude of at least about 1500 kilometers above the earth's surface. Circularly polarized electromagnetic radiation is transmitted at a first frequency substantially parallel to an earth's magnetic field line to excite electron cyclotron resonance heating in normally occurring plasma at an altitude of at least about 250 kilometers to generate a mirror force which lifts said plasma to said altitude of at least about 1500 kilometers. Heating is continued at a second frequency to expand the plasma to the apex of said field line whereupon at least some of the plasma is trapped and oscillates between mirror points on said lines. The plasma will be contained within adjacent field lines and will drift to form a shell of relativistic particles around a portion of the earth.

7 Claims, 2 Drawing Sheets



METHOD FOR PRODUCING A SHELL OF RELATIVISTIC PARTICLES AT AN ALTITUDE ABOVE THE EARTHS SURFACE

DESCRIPTION

1. Technical Field

The present invention relates to a method for altering a selected region of plasma normally existing at a substantial altitude above the earth's surface and more particularly relates to a method for producing a magnetically-trapped shell of high density plasma having relativistic particles therein.

2. Background Art

In the late 1950's, it was discovered that naturally-occurring belts exist at high altitudes above the earth's surface, and it is now established that these belts result from charged electrons and ions becoming trapped along the magnetic lines of force (field lines) of the earth's essentially dipole magnetic field. The trapped electrons and ions are confined along the field lines between two magnetic mirrors which exist at spaced apart points along those field lines. The trapped electrons and ions move in helical paths around their particular field lines and "bounce" back and forth between the magnetic mirrors. These trapped electrons and ions can oscillate along the field lines for long periods of time

In the past several years, substantial effort has been made to understand and explain the phenomena involved in belts of trapped electrons and ions and to explore possible ways to control and use these phenomena for beneficial purposes. For example, in the late 1950's and early 1960's, both the United States and U.S.S.R. detonated a series of nuclear devices of various yields to generate large numbers of charged particles at various altitudes, e.g., 200 kilometers (km) or greater. This was done in order to establish and study artificial belts of trapped electrons and ions. These experiments established that at least some of the extraneous electrons and ions from the detonated devices did become trapped along field lines in the earth's magnetosphere to form artificial belts which were stable for prolonged periods of time. For a discussion of these experiments see "The Radiation Belt and Magnetosphere", W. N. Hess, Blaisdell Publishing Co., 1968, pps. 155 et sec.

Other proposals which have been advanced for altering existing belts of trapped electrons and ions and/or establishing similar artificial belts include injecting charged particles from a satellite carrying a payload of radioactive beta-decay material or alpha emitters; and injecting charged particles from a satellite-borne electron accelerator. Still another approach is described in U.S. Pat. No. 4,042,196 wherein a low energy ionized gas, e.g. hydrogen, is released from a synchronous orbiting satellite near the apex of a radiation belt which is naturally occurring in the earth's magnetosphere to produce a substantial increase in energetic particle precipitation and, under certain conditions, produce a limit in the number of particles that can be stably trapped. This precipitation effect arises from an enhancement of the whistler-mode and ion-cyclotron mode interactions that results from the ionized gas or "cold plasma" injection.

It has also been proposed to release large clouds of barium in the magnetosphere so that photoionization will increase the cold plasma density, thereby producing electron precipitation through enhanced whistler-mode interactions.

However, in all of the above-mentioned approaches, the mechanisms involved in triggering the change in the trapped particle phenomena must be actually positioned within the affected zone, e.g., the magnetosphere, before they can be actuated to effect the desired change.

The earth's ionosphere is not considered to be a "trapped" belt since there are few trapped particles therein. The term "trapped" herein refers to situations where the force of gravity on the trapped particles is balanced by magnetic forces rather than hydrostatic or collisional forces. The charged electrons and ions in the ionosphere also follow helical paths around magnetic field lines within the ionosphere but are not trapped between mirrors as in the case of the trapped belts in the magnetosphere, as the gravitational force on the particles is balanced by collisional or hydrostatic forces.

In recent years, a number of experiments have actually been carried out to modify the ionosphere in some controlled manner to investigate the possibility of a beneficial result. For detailed discussions of these operations see the following papers: (1) Ionospheric Modification Theory; G. Meltz and F. W. Perkins; (2) The Platteville High Power Facility; Carrol et al.; (3) Arecibo Heating Experiments; W. E. Gordon and H. C. Carlson, Jr.; and (4) Ionospheric Heating by Powerful Radio Waves; Meltz et al., all published in Radio Science, Vol. 9, No. 11, November, 1974, at pages 885–888; 889–894; 1041–1047; and 1049–1063, respectively, all of which are incorporated herein by reference. In such experiments, certain regions of the ionosphere are heated to change the electron density and temperature within these regions. This is accomplished by transmitting from earth-based antennae high frequency electromagnetic radiation at a substantial angle to, not parallel to, the ionosphere's magnetic field to heat the ionospheric particles primarily by ohmic heating. The electron temperature of the ionosphere has been raised by hundreds of degrees in these experiments, and electrons with several electron volts of energy have been produced in sufficient numbers to enhance airglow. Electron concentrations have been reduced by a few percent, due to expansion of the plasma as a result of increased temperature.

In the Elmo Bumpy Torus (EBT) device, a major controlled fusion device at the Oak Ridge National Laboratory, all heating is provided by microwaves at the electron cyclotron resonance interaction. A ring of hot electrons is formed in the magnetic mirror by a combination of electron cyclotron resonance and stochastic heating. In the EBT, the ring electrons are produced with an average "temperature" of 250 kev (2.5×10^9 K) and a plasma beta between 0.1 and 0.4 ; see, "A Theoretical Study of Electron - Cyclotron Absorption in Elmo Bumpy Torus", Batchelor and Goldfinger, Nuclear Fusion, Vol. 20, No. 4 (1980) pps. 403–418.

Electron cyclotron resonance heating has been used in experiments on the earth's surface to produce and accelerate plasmas in a diverging magnetic field. Kosmahl et al. showed that power was efficiently transferred from the electromagnetic waves and that a fully ionized plasma was accelerated with a divergence angle of roughly 13 degrees. Optimum neutral gas density was 1.7×10^{14} per cubic centimeter; see, "Plama Acceleration with Microwaves Near Cyclotron Resonance",

Kosmahl et al., Journal of Applied Physics, Vol. 38, No. 12, November, 1967, pps. 4576–4582.

It has heretofore been recognized that an intense focused beam of charged or neutral particles (e.g., plasma) can carry a potentially destructive amount of energy and is capable under certain circumstances of melting a hole in a piece of metal or of damaging even shielded electronic circuits. Recently, proposals have been set forth to exploit such particle beams as possible defense mechanisms to be used to protect against offensive missiles which may be launched by a hostile power; see "Particle-Beam Weapons"; J. Parmentola and K. Tsipis; Scientific American, April, 1979, Vol. 240, No. 4, which is incorporated herein by reference.

In such proposals, a particle accelerator is mounted in a satellite in an earth orbit at a 1000 km altitude and, when actuated, will increase the kinetic energy of a large number of individual atomic ions or subatomic charged particles and then direct them collectively at a target. A typical accelerator consists of a source of particles, a device for injecting the particles into the accelerator, and a series of accelerating sections. Every particle that strikes a target will transfer some of its energy to the material of the target. Given a large enough number of particles hitting the target in a short enough time, the deposited energy can become great enough to burn a hole in the "skin" of the target (e.g., missile) to denotate the chemical-explosive "trigger" of a warhead or to disrupt the electronics (e.g., guidance controls) inside the target vehicle. However, in these proposals, the accelerator has to be placed in orbit to generate the required "beam" of charged particles, and has to be accurately placed so that the beam can be aimed directly at the target.

DISCLOSURE OF THE INVENTION

This invention provides a method for establishing an upper region of a high density (i.e., electron concentration), high energy plasma at a selected altitude, e.g., at least about 1500 km, above the surface of the earth. Plasma (i.e., charged particles) which normally exists at a lower region, e.g., altitude of at least about 250 km, is excited by first electron cyclotron resonance heating to thereby increase the charged particle energy. This is done by transmitting circularly polarized electromagnetic radiation from a point at or near the location where a naturally-occurring dipole magnetic field (force) line intersects the earth's surface. The radiation is deliberately transmitted at the outset in a direction substantially parallel to and along the field line which extends upwardly through the region or regions of plasma to be altered. The radiation is transmitted at a first frequency, e.g., from about 1000 to about 3600 kilohertz (kHz) based on the gyrofrequency of the charged particles in the lower regions. When applied to the plasma in said region, the radiation excites electron cyclotron resonance within the plasma to heat and accelerate the charged particles in their respective helical paths around and along the field line. This increase in energy causes ionization of neutral particles which then become a part of the plasma thereby increasing the charged particle density of the plasma.

This first electron cyclotron resonance heating is carried out at sufficient power levels to allow the plasma to generate a mirror force which forces the charged electrons of the altered plasma upward along the force line to said upper region.

Circularly polarized electromagnetic radiation of a second frequency (e.g., from about 20 to about 1800 kHz) is employed to excite a second electron cyclotron resonance heating in the plasma at the level of said upper region to further and further ionize said plasma. This heating is continued until the plasma has expanded to the apex of said divergent magnetic field lines at which time at least some of the plasma is trapped along said field lines and oscillates between magnetic mirror points on said lines. As energy is absorbed by the trapped electrons by continued second electron cyclotron resonance heating, the mirror points of the particles forming the altered plasma will be raised from their original positions in the lower region to the point in the upper region where said second electromagnetic radiation is being absorbed. Further, as trapped particles oscillate back and forth between the hemispheres, they will be heated stochastically since they pass repeatedly through the heating region, that is the said upper region. The stochastic heating will be continued until the electron energies reach the range of from about 2 to about 5 Mev, at which the electrons are relativistic because of the electron masses having been increased substantially due to their high velocities. This increases the density or electron concentration of the trapped plasma to 10^9 per cubic centimeter.

The plasma will be confined between adjacent field lines and will form a shell of relativistic particles therebetween as these particles naturally "drift" around the earth. The shell so formed may be used as an anti-missile shield. The high energy, relativistic particles in the shell will collide with any missile passing therethrough to give up energy which, in turn, will damage or destroy the missile.

BRIEF DESCRIPTION OF THE DRAWINGS

The actual construction, operation, and apparent advantages of the present invention will be better understood by referring to the drawings in which like numerals identify like parts and in which:

FIG. 1 is a simplified, schematical view of the earth (not to scale) and a magnetic field (force) line along which the present invention is carried out;

FIG. 2 is a simplified, idealized representation of a physical phenomenon involved in the present invention; and

FIG. 3 is a simplified, perspective view of a high intensity, plasma shell formed in accordance with the present invention.

BEST MODES FOR CARRYING OUT THE INVENTION

The earth's magnetic field is somewhat analogous to a dipole bar magnet. As such, the earth's magnetic field contains numerous divergent field or force lines, each line intersecting the earth's surface at two points on opposite sides of the equator. The field lines which intersect the earth's surface near the poles have apexes which lie at the furthest points in the earth's magnetosphere while those closest to the equator have apexes which reach only the lower portion of the magnetosphere and below.

In both the earth's ionosphere and the magnetosphere, plasma is present along these field lines. This plasma consists of equal numbers of positively and negatively charged particles (i.e., electrons and ions) which are guided by the field line. It is well established that a charged particle in a magnetic field gyrates about field

lines; the center of gyration at any instance being called the "guiding center" of the particle. As the gyrating particle moves along a line of force in a uniform field, it will follow a helical path about its guiding center, which moves linearly along the field line. Electrons and ions both follow helical paths around a field line but rotate in opposite directions. The frequencies at which the electrons and ions rotate about the field line are called gyromagnetic frequencies or cyclotron frequencies because they are identical with the expression for the angular frequencies of gyration of particles in a cyclotron. The cyclotron frequency of ions in a given magnetic field is less than that of electrons, in inverse proportion to their masses.

If the particles which form the plasma along the earth's field lines continued to move with a constant pitch angle, often designated "alpha", they would soon impact on the earth's surface; pitch angle alpha being defined as the angle between the direction of the earth's magnetic field and the velocity (V) of the particle. However, in converging force fields, the pitch angle does change in such a way as to allow the particle to turn around and avoid impact. Consider a particle moving along a field line down toward the earth. It moves into a region of increasing magnetic field strength and therefore sine alpha increases. But sine alpha can only increase to 1.0, at which point, the particle turns around and starts moving up along the field line, and alpha decreases. The point at which the particle turns around is called the mirror point, and there alpha equals ninety degrees. This process is repeated at the other end of the field line where the same magnetic field strength value B, namely Bm, exists. The particle again turns around and this is called the "conjugate point" of the original mirror point. The particle is therefore trapped and bounces between the two magnetic mirrors. The particle can continue oscillating in space in this manner for long periods of time. The actual place where a particle will mirror can be calculated from the following:

$$\sin^2 \text{alpha}_o = B_o/B_m \quad (1)$$

wherein:

alpha_o = equatorial pitch angle of particle

B_o = equatorial field strength on particular field line

B_m = field strength at the mirror point

Recent discoveries have established that there are substantial regions of naturally trapped particles in space which are commonly called "trapped radiation belts". These belts occur at altitudes greater than about 500 km and accordingly lie in the magnetosphere and mostly above the ionosphere.

The ionosphere, while it may overlap some of the trapped-particle belts, is a region in which hydrostatic forces govern its particle distribution in the gravitational field. The motion of the ionosphere is governed by both hydrodynamic and electrodynamic forces. While there are few trapped particles in the ionosphere, nevertheless, plasma is present along field lines in the ionosphere. The charged particles which form this plasma move between collisions with other particles along similar helical paths around the field lines and although a particular particle may diffuse downward into the earth's lower atmosphere or diverge from its original field line due to collisions with other particles, these charged particles are normally replaced by other available charged particles. The electron density or concentration (N_e) of the plasma will vary with the actual conditions and locations involved. Also, neutral particles, ions, and electrons are present in proximity to the field lines.

As known in plasma physics, the characteristics of a plasma can be altered by adding energy to the charged particles or by ionizing additional particles to increase the density of the plasma. One way to do this is by heating the plasma which can be accomplished in different ways, e.g., ohmic, magnetic compression, shock waves, magnetic pumping, electronic cyclotron resonance, and the like.

Since electron cyclotron resonance heating is involved in the present invention, a brief discussion of same is in order. Increasing the energy of electrons in a plasma by invoking electron cyclotron resonance heating, is based on a principle similar to that utilized to accelerate charged particles in a cyclotron. If a plasma is confined by a static axial magnetic field of strength B, the charged particles will gyrate about the lines of force with a frequency given, in hertz, as $f_g = 1.54 \times 10^3 B/A$, where: B = magnetic field strength in gauss, and A = mass number of the ion.

Suppose a time-varying field of this frequency is superimposed on the static field B confining the plasma, by passage of a radiofrequency current through a coil which is concentric with that producing the axial field, then in each half-cycle of their rotation about the field lines, the charged particles acquire energy from the oscillating electric field associated with the radio frequency. For example, if B is 10,000 gauss, the frequency of the field which is in resonance with protons in a plasma is 15.4 megahertz.

As applied to electrons, electron cyclotron resonance heating requires an oscillating field having a definite frequency determined by the strength of the confining field. The radio-frequency radiation produces time-varying fields (electric and magnetic), and the electric field accelerates the charged particle. The energized electrons share their energy with ions and neutrals by undergoing collisions with these particles, thereby effectively raising the temperature of the electrons, ions, and neutrals. The apportionment of energy among these species is determined by collision frequencies. For a more detailed understanding of the physics involved, see "Controlled Thermonuclear Reactions", Glasstone and Lovberg, D. Van Nostrand Company, Inc., Princeton, N.J., 1960 and "The Radiation Belt and Magnetosphere", Hess, Blaisdell Publishing Company, 1968, both of which are incorporated herein by reference.

Referring now to the drawings, the present invention provides a method for altering an upper region of plasma which lies along a field line when it passes through the ionosphere and/or magnetosphere. FIG. 1 is a simplified illustration of the earth 10 and one of its essentially dipole magnetic force or field lines 11. As will be understood, line 11 may be any one of the numerous naturally existing field lines and the actual geographical locations 13 and 14 of line 11 will be chosen based on the particular operation to be carried out. The actual locations at which field lines intersect the earth's surface is documented and is readily ascertainable by those skilled in the art.

Line 11 passes through region R_1 which lies at an altitude, e.g., at least about 250 kilometers (km) above the earth's surface. As explained above, plasma will be present along line 11 within region R_1 and is represented by the helical line 12. Plasma 12 is comprised of charged

particles (electrons and ions) which rotate about opposing helical paths along line 11.

Antenna 15 is positioned as close as practical to the location 14 where line 11 intersects the earth's surface. Antenna 15 may be of any known construction for high directionality, for example, a phased array, beam spread angle (θ) type; see "The MST Radar at Poker Flat, Alaska", Radio Science, Vol. 15, No. 2, March–April 1980, pps. 213–223, which is incorporated herein by reference. Antenna 15 is coupled to transmitter 16 which generates high frequency electromagnetic radiation at a wide range of discrete frequencies, e.g., from about 20 to about 7200 kHz.

Transmitter 16 is powered by power generator means 17 which is preferably comprised of one or more commercial electrical generators such as magnetogydrodynamic, turbine, fuel cell, electrogasdynamic generators, and the like. Some embodiments of the present invention require large amounts of power, e.g., up to 10^{10} watts, in continuous wave or pulsed power. Generation of the needed power is within the state of the art. The electrical generators can be powered in any known manner, e.g., nuclear reactors, hydroelectric facilities, hydrocarbon fuels in areas where large supplies are available, and the like.

In FIG. 1, a first step of the present invention is illustrated where a selected region R_1 of plasma 12 is altered by electron cyclotron resonance heating to accelerate the electrons of plasma 12, which are following helical paths along line 11.

To accomplish this result, electromagnetic radiation is transmitted at the outset, essentially parallel to field line 11 via antenna 15 as circularly polarized radiation wave 20 (right-hand circularly polarized in the Northern Hemisphere and left-hand in the Southern Hemisphere). Wave 20 has a frequency which will excite electron cyclotron resonance with plasma 12 at its initial or original altitude. This frequency (from about 20 to about 7200 kHz) will vary depending on the electron cyclotron resonance or harmonic of the resonance of region R_1 which, in turn, can be determined from available data based on the altitude of region R_1, the particular field line 11 being used, the strength of the earth's magnetic field, etc. Also, for any given application, there will be a threshhold (minimum power level) which is needed to produce the desired result. The minimum power level is a function of the level of plasma production and movement required, taking into consideration any loss processes that may be dominant in a particular plasma or propagation path.

As electron cyclotron resonance is established in plasma 12, energy is transferred from the electromagnetic radiation 20 into plasma 12 to heat and accelerate the electrons, and subsequently ions and neutrals. As this process continues, neutral particles which are present within R_1 are ionized and absorbed into plasma 12 and this increases the electron and ion densities of plasma 12. As the electron energy is raised to values of about 1 kilo electron volt (kev), the generated mirror force (explained below) will direct the excited plasma 12 upward along line 11 into a second region R_2 which is at an altitude higher than that of R_1.

Plasma acceleration results from the force on an electron produced by a non-uniform static magnetic field ($\bar{B}$). The force, called the mirror force in this context, is given by

$$F = -\mu \nabla B \qquad (2)$$

where μ is the electron magnetic moment and ∇B is the gradient of the magnetic field, μ being further defined as:

$$W_\perp/B = n.V_\perp^2/2B$$

where $W_\perp$ is the kinetic energy in the direction perpendicular to that of the magnetic field lines and B is the magnetic field strength at the line of force on which the guiding center of the particle is located. The force as represented by equation (2) is the force which is responsible for a particle obeying equation (1).

Since the magnetic field is divergent in region R_1, it can be shown that the plasma will move upwardly from the heating region as shown in FIG. 1 and further it can be shown that

$$\tfrac{1}{2}M_e V_{e\perp}^2(x) \simeq \tfrac{1}{2}M_e V_{e\perp}^2(Y) + \tfrac{1}{2}M_i V_{i\parallel}^2(Y) \qquad (3)$$

where the left hand side is the initial electron transverse kinetic energy; the first term on the right is the transverse electron kinetic energy at some point (Y) in the expanded field region, while the final term is the ion kinetic energy parallel to B at point (Y). This last term is what constitutes the desired ion flow. It is produced by an electrostatic field set up by electrons which are accelerated according to Equation (2) in the divergent field region and pulls ions along with the them. Equation (3) ignores electron kinetic energy parallel to B because $V_{e\parallel} \simeq V_{i\parallel}$, so the bulk of parallel kinetic energy resides in the ions because of their greater masses. For example, if an electromagnetic energy flux of from about 0.1 to about 1 watts per square centimeter is applied to region R_1, whose altitude is about 250 km, a plasma having a density (N_e) of 10^9 per cubic centimeter and an ion energy of about 3 ev will be generated and moved upward to region R_2, which has an altitude of about 1500 km. The movement of electrons in the plasma is due to the mirror force while the ions are moved by ambipolar diffusion (which results from the electrostatic field). This effectively "lifts" a layer of plasma 12 from R_1 to the higher elevation R_2.

FIG. 2 is an idealized representation of movement of plasma 12 upon excitation by electron cyclotron resonance within the earth's divergent force field. Electrons (e) are accelerated to velocities required to generate the necessary mirror force to cause their upward movement. At the same time neutral particles (n) which are present along line 11 in region R_1 are ionized and become part of plasma 12. As electrons (e) move upward along line 11, they drag ions (i) with them but at an angle θ of about 13 degrees to field line 11. The ions, in turn, will drag the neutrals n along by colliding with them. Also, any particulates that may be present in region R_1, will be swept upwardly with the plasma. As the charged particles of plasma 12 move upward, other particles such as neutrals within or below R_1, move in to replace the upwardly moving particles. These neutrals, under some conditions, can drag with them charged particles from adjoining regions.

Referring now to FIGS. 1 and 3, plasma 12 having a density of 10^9 per cubic centimeter and an ion energy of about 3 ev is formed in region R_2 by heating plasma 12 within region R_1 and moving it upward along field line 11 (e.g., earth field line L_4) to region R_2 which lies at an altitude of about 1500 km. To raise the necessary volume of plasma for the present invention, a total energy

of 10^{15} joules will be applied through the electron cyclotron resonance heating of region R_1. After the plasma **12** is raised to region R_2, circularly polarized electromagnetic radiation having a second, different frequency (e.g., about 1.0 MHz) is transmitted to upper region R_2 where it further excites electron cyclotron resonance heating within plasma **12** in region R_2. This radiation having a second different frequency can be supplied by adjusting the frequency of the original radiation used in region R_1, and/or supplied by way of separate source of radiation. By further exciting the electrons to 10 ev per electron, plasma **12** will expand along line **11** to apex point C. When this occurs, a substantial portion of plasma **12** becomes trapped along line **11** and oscillates thereon between mirror points M_B. The mirror points for the trapped particles of the altered plasma will be raised from their original mirror points M_A (FIG. 1) in region R_1 to mirror point M_E in the upper region R_2 by the continued second resonance cyclotron resonance heating as it is being applied to the particles in the upper region R_2. The oscillation of the particles will then allow additional heating by stochastic heating which is associated with trapped and oscillating particles; see "A New Mechanism for Accelerating Electrons in the Outer Ionosphere" by R. A. Helliwell and T. F. Bell, Journal of Geophysical Research, Vol. 65, No. 6, June, 1960, which is incorporated herein by reference.

The continued excitation of electron cyclotron resonance heating in region R_2 coupled with the stochastic heating that occurs due to oscillation on field line **11** will excite the electrons of plasma **12** to energies of from about 2 to about 5 Mev thereby making them relativistic (i.e., particles whose mass has increased due to high velocities). This combined heating effect is similar to Elmo Bumpy Torus (EBT) heating. As plasma **12** oscillates on line **11** above mirror points M_B, it is contained between divergent field lines **11***a* and **11***b* (FIG. 3) which lie adjacent line **11**, as will be understood by those skilled in the art.

Particles trapped on a earth's magnetic field will naturally migrate or "drift" laterally around the earth's circumference following a path defined by a particular magnetic field shell (e.g., L_4) which is present at substantially the same latitude around the earth. The plasma will drift until a shell **20** is formed having a width (w) in region R_2. The total energy to generate a shell **20** of relativistic particles having an average width in region R_2 of 100 kilometers and a particle density of 10^9 per cubic centimeter and a particle energy of 6 Mev will be about 10^{19} joules.

Shell **20**, once formed, provides an anti-missile, relativistic electron barrier that will detonate or severly damage the electronic system of any missile that passes therethrough. As illustrated in FIG. 3, an intercontinental ballistic missile (ICBM) that is launched along a trajectory such as shown by the heavy dashed line **25**, will have to pass through shell **20** twice on its way to target X (once on its ascent and once upon reentry).

As the missile passes through shell 20, the (high intensity (e.g., 6 Mev) particles of plasma **12** penetrate the missile. As each particle does this, it loses energy principally by transferring energy to electrons in the missile by a series of elastic collisions giving a cascade of electrons which leaves the direction of the motion largely undisturbed. Eventually, the energy lost in the material of the missile manifests itself as heat thereby raising the temperature of the material where the particles collide. At the density and energy levels of plasma **12** within shell **20**, the rate of energy deposition (i.e., heating) will be greater than can be dissipated and the material will melt or crack under thermal stress. Detectable damage will result either from burning through the walls of the missile's fuel container, damaging the electronic systems of the missile, or from detonation of the chemical-explosive triggers of the missile's warhead; the latter requiring about 200 joules per cubic centimeter of material impacted.

It can be seen from the above, that by generating a shell **20** of high density, relativistic particle plasma, an effective defensive shield can be provided to guard against offensive missiles.

I claim:

1. A method for establishing a region of a plasma at an altitude of at least about 1500 km above the surface of the earth, said method comprising:

providing at least one source of circularly polarized electromagnetic radiation having a first frequency in the range of from about 1800 to about 3600 kHz;

transmitting said electromagnetic radiation from said earth's surface substantially parallel to and along at least one of the earth's naturally occurring and diverging magnetic field lines and focused so as to provide a power flux of about 0.1 to about 1 watt per square centimeter at an altitude of at least 250 km;

adjusting said first frequency of said electromagnetic radiation to a value which will excite a first electron cyclotron resonance within plasma which normally exists adjacent said field line at a first altitude of at least about 250 km whereby said electron cyclotron resonance causes heating and further ionization of said plasma to form a plasma having an ion energy of at least 3 ev;

continuing to excite said first electron cyclotron resonance for a time between 0.1 and 1200 seconds sufficient to cause movement of said plasma upward along said diverging magnetic field lines from said first altitude to said region at said altitude of at least about 1500 km;

providing electromagnetic radiation having a second frequency in the range of from about 20 to 1800 kHz and different from said first frequency and which will excite further electron cyclotron resonance in said plasma after it has moved to said region to further heat and to further ionize said plasma and to raise the mirror points of said plasma; and

continuing to excite said second electron cyclotron resonance in said plasma to produce relativistic electrons in said plasma having an electron energy up to 20 million electron volts.

2. The method of claim **1** wherein the excitation of said first electron cyclotron resonance is continued for a sufficient time of about 1200 seconds to expand said plasma upward along said diverging magnetic field lines to the apex of said lines to thereby trap at least some of said plasma which causes said plasma to oscillate between magnetic mirror points on said field lines and to be further heated by stochastic heating.

3. The method of claim **2** wherein said second electron resonance is continued until the electron concentration of said trapped plasma reaches at least about 10^9 per cubic centimeters.

4. The method of claim 2 wherein the energy of the relativistic electrons in said trapped plasma is at least about 2 million electron volts.

5. The method of claim 4 wherein said first electron cyclotron resonance is continued until a shell of relativistic electrons is formed by natural drift of said electrons around the earth's circumference.

6. The method of claim 5 wherein the width of said shell is at least about 100 km.

7. The method of claim 6 wherein said shell is formed as an anti-missile shield.

* * * * *

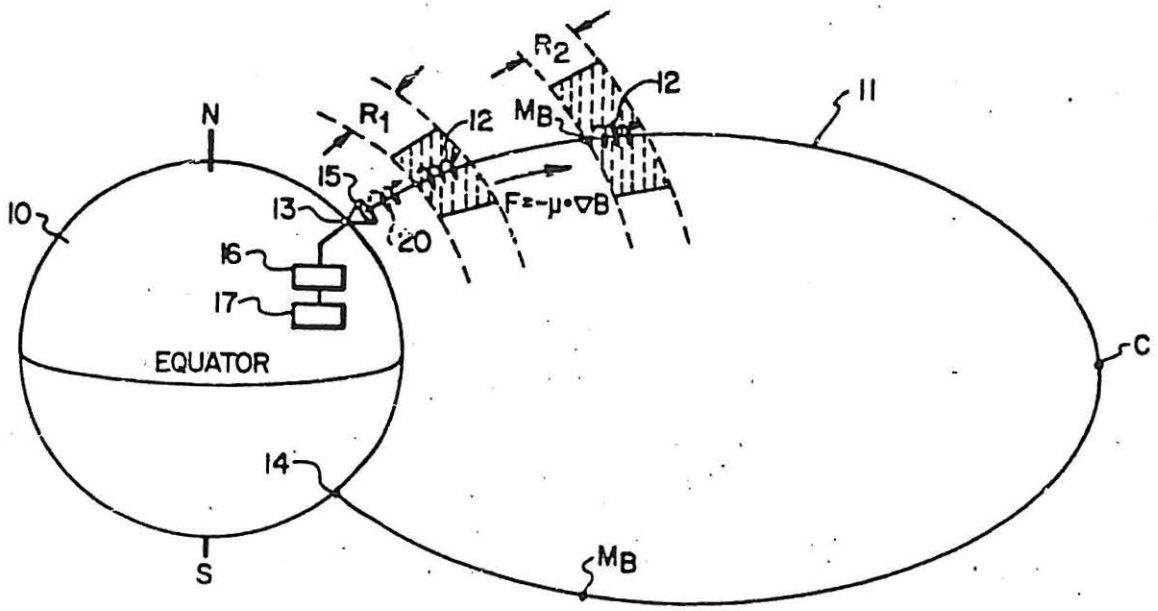

R2
12
11
N
R1
12
MB
15
F=-μ•∇B
13
10
20
16
17
EQUATOR
C
14
S
MB

FIG. 1

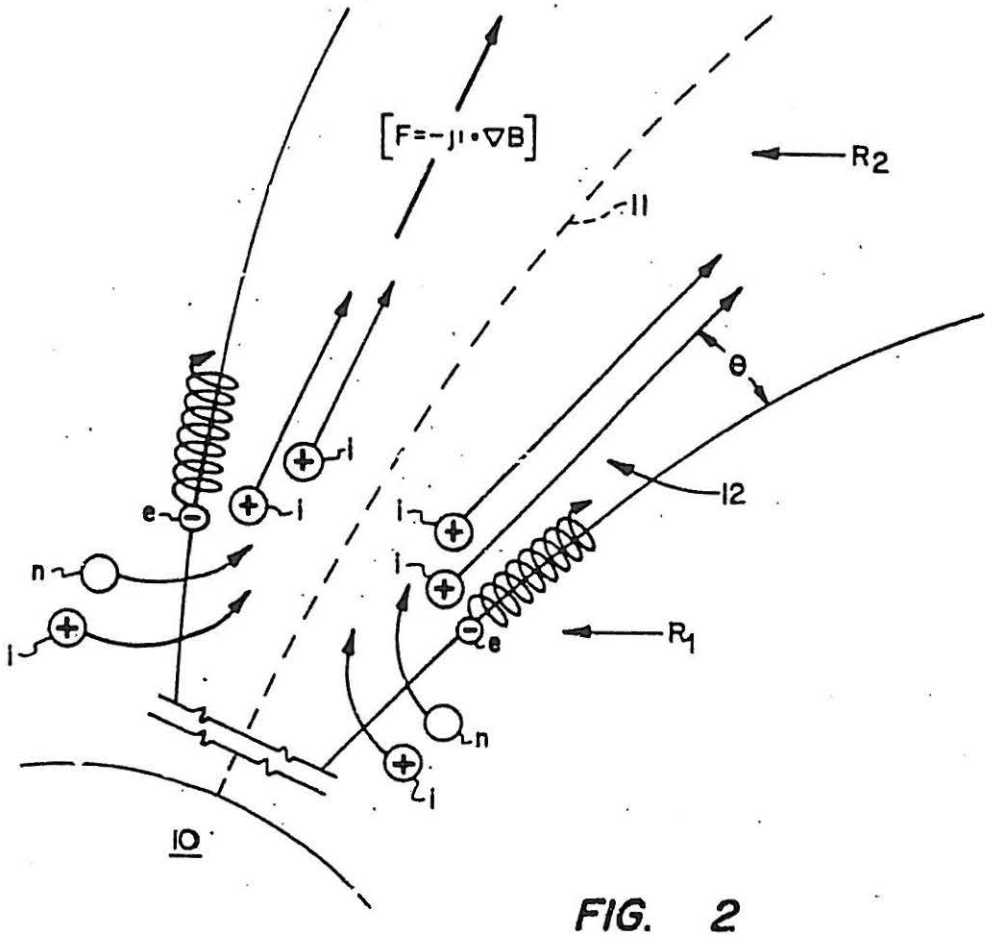

[F=-μ•∇B]
R2
11
θ
12
e
i
n
R1
10

FIG. 2