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"Sagnac" effect: A century of Earth-rotated interferometers

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The earliest prediction of the Sagnac effect, and of the possibility of detecting the Earth's rotation with an interferometer of square kilometer area, is by Lodge (1893, 1897). We illustrate the extraordinary range of theoretical motivations for the experimental study of the Sagnac effect, starting with previously unpublished correspondence between Lodge and Larmor, and ending with present (and planned) ring interferometer experiments whose sensitivity to the Earth's rotation is of the order of parts per million (billion, respectively).

I. EARLY HISTORY OF SAGNAC INTERFEROMETERS

In 1913, Georges Sagnac published[1] accounts of the effect of a rotation of angular frequency $\mathbf{\Omega}$ on the time difference δt and fringe phase shift $\delta\phi$ in a ring interferometer of area $\mathbf{A}$

$$\delta t=\frac{4\mathbf{\Omega}\cdot\mathbf{A}}{v^2},\quad \delta\phi=\frac{8\pi\mathbf{\Omega}\cdot\mathbf{A}}{\lambda v},\tag{1}$$

where v is the undragged velocity of the light beam. Sagnac had predicted this effect in various earlier papers.[2] The enduring significance of the 1913 papers lies in the fact that Sagnac was the first person to report an experimental observation of this shift, in his case for a small polygonal interferometer mounted on a turntable, and its interpretation within the framework of an ether theory. The area of his interferometer was 0.0860 m^2, the rotation rate of order 2 Hz, and the resulting fractional fringe shift 0.07 ± 0.01.

This was not the only experiment performed or contemplated by Sagnac. For example, he had already checked—and for an interferometer with a perimeter of 20 m—that no "whirling of the ether" (radial velocity gradient with nonzero curl) is detected when the ring is vertical, with a precision of 1/1000 of a fringe. (For a vertical ring oriented north–south, $\mathbf{\Omega}$ and $\mathbf{A}$ are perpendicular, and no Sagnac effect would be expected. However a vertical ring mounted east–west in midlatitudes can see the Earth rotation in principle.)

In his first 1913 paper, as well as mentioning this null experiment and announcing his successful turntable experiment, Sagnac also predicted that an effect should arise in principle from Earth rotation. He stated that "in a horizontal optical circuit, at latitude α, the diurnal rotation of the Earth should, if the ether is immobile, produce a relative whirling of the ether of which the degree is $4\pi\sin\alpha/T$ where T is the length of a sidereal day, 86164 seconds. The result is notably less than the above limit of 1/1000 which I have established for a vertical circuit. I hope," wrote Sagnac, "to be able to determine whether the slight corresponding optical whirling effect exists or not." But he never achieved his wish; as his calculation showed, a prodigiously large interferometer would be required.

Partial anticipations of any significant advance in physics are the rule, not the exception. All physicists stand with Newton on the shoulders of giants. A new idea may appear to be forged apparently independently, but its advent is usually ripe for more than one worker. It is now well known (see Post[3] and Dieks[4]) that the Sagnac effect had been anticipated on the theoretical side by Michelson[5] and on the experimental side by Harress.[6] However, neither had linked experiment with an adequate theory and there is no evidence that either reference was known to Sagnac.

On the experimental side, Harress[6] was studying the effect of Fresnel drag in a dispersive glass, and for convenience had used rotation for the motion. After a difficult development, including a disastrous accident in which his first carefully constructed circle of dispersing prisms was destroyed[7]—a hazard not unknown to other early workers[8] in Fresnel drag experiments—he obtained a result which included an unexpected and to him inexplicable bias in the fringe shift. This tragedy was soon followed by his early death. It was realized simultaneously with, but independently from, Sagnac's work that Harress's unexplained fringe shift was that of Eq. (1). In hindsight, Harress's observation was a more accurate observation of the Sagnac effect than Sagnac's own later experiment. Moreover it demonstrates that the Sagnac fringe shift is unaffected by refraction.[3]

Excellent summaries of various parts of the complicated, and in places obscure, history and interpretation of the Sagnac effect are given by Post,[3] Heer,[9] Schleich *et al.*,[10] and by Hasselbach and Nicklaus.[11] Our account to some extent complements these, as also those of Chow *et al.*,[12] MacKenzie,[13] and Stedman.[14]

On the theoretical side, Michelson[5] had published a paper in which in quick succession he mentions several logically distinct if related matters. For example, Michelson questions the possibility of being able to measure the one-way speed of light, making his paper an early contribution to a continuing debate.[15,16] Michelson notes in particular that Newcomb in 1880 had pointed out the flaws in a proposal by Wien to measure the one-way speed of light. Michelson then predicted by contrast the feasibility of comparing the speeds of light in traversing a closed polygonal path in opposite directions, e.g., traveling in opposite directions around the Equator (this may be the first mention in physics of the ultimate

Earth-bound particle accelerator). The role of such procedures as tests of relativity theory has recently been clarified and revitalized (see, e.g., Vetharaniam *et al.*).[17] Michelson immediately noted and quantified the potential ("Sagnac") effect of Earth rotation in inducing such an apparent speed change and fringe shift. He boldly suggested that an interferometer with an area of one square kilometer should suffice for its measurement. Finally he speculated on the likely size of an interferometer to detect the rotation of the Earth around the Sun, and came up with the answer of 100 square kilometers, which is still puny beside his hypothesized Equatorial interferometer. Let no one imagine that devices such as the (successful) LEP at CERN, or the (abandoned) SSC, are relatively novel dreams.

Such unbridled speculation is the stuff of progress in science. Michelson, with Gale and Pearson, later actually performed the square-kilometer experiment[18] (to be precise, 2010 ft by 1113 ft and so 0.21 km^2) in Clearing, IL, using 12-in.-diam water pipes evacuated to 12 mm of mercury, and successfully confirmed his prediction of an interferometric fringe shift from Earth rotation in accordance with Eq. (1); for some other information and photographs, see Shankland.[19] The heroic nature of this experiment has been highlighted by Telegdi.[20] This experiment was motivated by the suggestion of Silberstein[21] that relativistic or ether-theoretic frame dragging might affect the result, in that Eq. (1) might prove to be invalid for the action of the Earth rotation: the ether might be entrained by the rotation of the Earth but not by that of a small laboratory mass. Michelson therefore appears to deserve credit for the first prediction, if not the first demonstration, of the Sagnac effect.

However, such questions had been raised publicly or privately well before Michelson's 1904 paper. In articles published in 1893 and 1897, Sir Oliver Lodge[22] clearly anticipates the Sagnac result in general as well as the associated possible detection of Earth rotation in an interferometer of area 1 square kilometer. Heer,[9] Wilkinson,[23] and Hasselbach and Nicklaus[11] are the only authors we have found who give Lodge credit for anticipating the Sagnac effect.[24] We offer some further material in support of this. The theoretical origin of Lodge's predictions is clarified here from previously unpublished correspondence between Sir Joseph Larmor and Lodge during 1897. Quotations from this correspondence and from Lodge's publications are given in the Appendix to clarify the level of understanding achieved in 1897. Larmor was familiar with Lodge's 1897 paper through being one of the referees for the Royal Society (Poynting was the other).[25] It was shortly after his report recommending publication in the Society's *Philosophical Transactions* that Larmor initiated his correspondence with Lodge.

This discussion centered on and was motivated by Lodge's "whirling machine," an instrument in which metal plates were rotated at high speed (in an effort to "drag the ether") in the vicinity of a Fizeau interferometer whose area was of the order of one square meter.[22,26–29] This was no mean device, two blades each with a diameter of 1 m being rotated at 3000 rpm, the interferometer light paths being sandwiched between them. A fringe shift proportional to rotational speed was sought. This might appear to be a failsafe experiment. However Lodge, as a careful experimenter, mounted his interferometer on a mechanically independent "stone altar" tied to the sandstone underneath his Liverpool laboratory, and was eventually able to eliminate all spurious fringe shifts, leaving him with "not an iota" of an effect[27] (to an accuracy of 1/300 of a fringe). Incidentally, Michelson also had found the necessity of placing such interferometers on a stable base. Newcomb had arranged for Michelson a leave of absence from his Navy duty, and he made an early attempt at a "Michelson–Morley" experiment using a stone pier in Helmholtz's laboratory in Potsdam; the experiment was aborted because of the 1881 Potsdam street traffic.[30] Michelson then resorted to cellars or basements, and to floating large stone platforms in mercury.

In the course of analyzing his experiment and correspondence with Larmor in particular, Lodge wondered about the effect of Earth rotation on the ether and so on his interferogram. Larmor's initial reaction was delightfully barbed: "It is suggested that you are going to reverse the rotation of the earth in order to get an interference effect around your circuit." This reflected a very obvious problem which Telegdi[20] called "the devil:" how does one calibrate a permanent bias? Michelson also noted this problem in 1904, and (being Michelson) then solved it elegantly in his 1925 experiment by utilizing a smaller interferometer built into the larger one for calibration of the fringe position. Michelson himself was not overly enthusiastic about his work with Gale; he embarked on it reluctantly in deference to the urgings of relativists such as Silberstein "whose mathematical arguments he modestly professed he was unable to refute,"[31] and subsequently caustically remarked[19,31] that the experiment "only shows that the earth rotates on its axis." And its result agrees with Fresnel's old fixed ether theory, as well as the special and general theories of relativity. (Sagnac had considered his experiment to be a "direct manifestation" of the ether, but this was quickly refuted.)[10] For all that, Einstein also found the technique of the experiment of great interest. In a letter to Shankland dated 17 September 1953,[19] Einstein said: "··· my admiration for Michelson's experiment is for the ingenious method to compare the location of the interference pattern with the location of the image of the light source. In this way he overcomes the difficulty that we are not able to change the direction of the earth's rotation." We note in the Appendix that Lodge also had a comment on this problem.

The discussion between Larmor and Lodge (see the Appendix) ranged over several allied matters. It included a clear prediction by Larmor in 1897 of what we would now interpret as the Sagnac effect and in the terms of Eq. (1); however, Lodge's 1893 analysis of dragging was readily adaptable, as Lodge noted in 1897, to give the same result. Originally, Lodge had focused on a possible dragging effect on a nonrotating interferometer of locally rotating matter. While Lodge and Larmor were discussing this within the now obsolete confines of an ether-theoretic model, a related effect is now indeed known and expected within the context of general relativity and is known as Lense–Thirring frame dragging. Its observation for the case of the Earth rotation is the goal of an experiment using mechanical gyros, the "Schiff gyro" experiment, long planned for a yet future Space Shuttle mission.[32] Some other techniques for its measurement are mentioned below. In a spherically symmetric model, the magnitude of the effective rotation rate of the dragged local Lorentz frame $\mathbf{\Omega}'$ appearing for $\mathbf{\Omega}$ on the right-hand side Eq. (1) is given by

$$\mathbf{\Omega}' = \frac{GI}{c^2R^3}\left(\frac{3\mathbf{R}}{R^2}(\mathbf{\Omega}\cdot\mathbf{R}) - \mathbf{\Omega}\right), \tag{2}$$

where I, $\mathbf{\Omega}$ are the moment of inertia and angular velocity of the rotating matter, and $\mathbf{R}$ is the displacement from its center

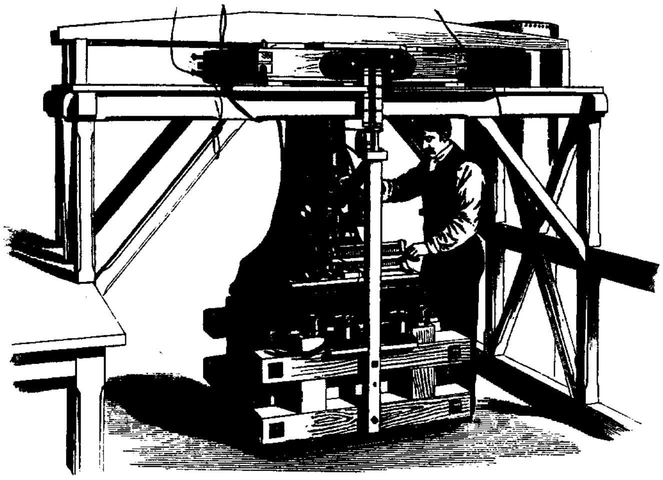

Fig. 1. The whirling machine of Lodge [reproduced from Fig. 11 of Lodge's 1893 paper (Ref. 22), by kind permission of the Royal Society of London]. The electric motor rotated two blades at the top, which are encased in this figure along with the interferometer. The latter is independently mounted to fit in the gap between the blades.

to that of the sensor. It may be regarded, among other things, as a gravitational analogue of Larmor's theorem, using the Larmor relationship $\Omega = qB/2m$ between rotation and magnetic field. This relationship itself is a useful translation for many situations in which rotation and magnetic field produce analogous effects.[33] For example, it helps in describing the magnetic ("London") field generated in superconductors or metals by such frame dragging. Proposals have been made to study the Lense–Thirring frame dragging using a pendulum at the South Pole,[34] and to study the associated Coriolis[35] or magnetic[36,37] effects directly, although as specified these are not yet practical.[38–40]

We estimate for interest the magnitude of the fringe shift expected in the case of Lodge's laboratory experiment by this frame dragging mechanism, and the magnitude of the effective rotation rate of the local Lorentz frame. The effectiveness of the rotation is scaled by the prefactor $GI/c^2R^3 \sim GM/Rc^2 = r_s/2R$, where r_s is the Schwarzschild radius and R the physical radius of the object. For the Earth, this prefactor at the surface is of order 10^{-10}. This defines the level at which relativistic effects are expected (see Sec. V).

In Lodge's 1893 experiments, two steel disks with a diameter of 1 m were rotated, with the interferometer light paths in the 2.5 cm gap (Fig. 1).[22] The disks were of unspecified mass and thickness; we assume the latter to be of order 5 mm. This suggests a prefactor of the order of 10^{-27}, and an expected Lense–Thirring or frame-dragging fringe shift of the order of 10^{-40} rad. In the 1897 experiments, Lodge increased the mass of the disk (to 0.75 ton) by raising the thickness to approximately 15 cm and also lowered the gap. However, the rotation rate was then necessarily reduced by a factor of 10. The Lense–Thirring effect was still undetectably small by many orders of magnitude.

The Lodge interferometer has an area of one square meter, and so marginally qualifies as what Ashcroft[41] has extolled as a "tabletop experiment." By this we mean an experiment whose small scale belies its wider interest and influence. By contrast, the 1925 Michelson, Gale, and Pearson experiment,[18] like CERN's LEP particle storage ring, clearly fails to qualify for an entry in Ashcroft's catalogue.

Also in 1897, Michelson[42,3] attempted unsuccessfully to detect Earth rotation in a ring interferometer. As in Sagnac's alternative experiment, his interferometer was vertical. In Michelson's case this was mounted east–west and covered a full circuit of a building, with the dimensions 200 ft×50 ft (or 60 m×15 m *high*). Since it was oriented east–west, in principle there would be a component of the Earth's angular velocity parallel to the area vector, and a Sagnac effect is possible. Michelson's null result (to an accuracy of 1/20 of a fringe) is consistent with this for an interferometer of this area. However Michelson did not associate the observable with a rotation; his rationale was to test whether the degree of dragging of the ether by the Earth in its motion was dependent on altitude, and in analyzing his experiment he hypothesized an exponential falloff of ether drag with altitude above the supposedly planar surface of the Earth. He concluded that his null result suggested that on such a model "the earth's influence on the ether extended to distances of the order of the earth's diameter." He commented: "Such a conclusion seems so improbable that one is inclined to return to ⋯ the hypothesis that the length of bodies is altered by their motion through the ether." By 1904 Michelson was probably aware of Lodge's earlier work; Lodge sent Michelson, along with many others including the Archbishop of Canterbury, a copy of his 1893 paper,[29] and both authors use similar words to select a square kilometer ring as appropriate for measuring the Sagnac effect of the Earth's rotation. However, in his 1925 paper, Michelson did not refer even to his own earlier work, and apparently[3] Michelson never attempted an experiment with a ring interferometer on a turntable. Incidentally, the final suggestion of Michelson,[5] that the orbital motion of the Earth round the Sun might be detectable in a sufficiently gargantuan ring interferometer, is not consistent with general relativity: a freely falling point object (the whole Earth, in this context) defines a local Lorentz frame.

II. ALTERNATIVE ROTATION-SENSING INTERFEROMETERS; THEORETICAL ASPECTS

From Eq. (1), the Sagnac effect is easier to see if the velocity of the waves is reduced, as for matter waves; particularly for cold neutrons and atoms. Sagnac tabletop and turntable-based experiments have been performed with superconducting interferometers,[43] electrons,[11] and recently for coherent beams of atoms.[44] Prior to these developments, the very great potential of atomic interferometry for such topics as "measurements of the Lense–Thirring and de Sitter precessions, ⋯ measurement of gravitational gradients ⋯ navigations, geology, surveying and the analysis of structures" has been discussed by Clauser.[45] A long-standing discussion with several component debates on the role of dispersion in the Sagnac effect and with reference to neutron as well as photon experiments is admirably reviewed by Hasselbach and Nicklaus,[11] and is continuing.[46,47]

The Sagnac effect of the Earth rotation has been rendered visible even in neutron interferometers.[48] The tabletop here is extraordinarily small (square centimeters), although it is heavily irradiated. The Sagnac effect has also finally been seen optically with phase interferometers of similar overall dimensions in connection with some comparatively recent work on high temperature superconductors;[49] the use of multiple turns of optical fiber enhances the effective area.

The theoretical associations of the Sagnac effect are ubiquitous. A recent and helpful survey of this also is given by

Hasselbach and Nicklaus.[11] The extent to which the original derivations of the Sagnac effect endorse an ether theoretic model has been debated,[3,4,11] but it is now generally recognized that the prediction of Eq. (1) is remarkably robust to the assumed theoretical framework, at least for spinless particles. For example, it applies even under angular acceleration;[50] incidentally, neither linear velocity nor linear acceleration affect the result or indeed are detectable by a ring. It can be derived from the special relativistic Doppler effect at the mirrors[51] or from general relativity,[3,52–54] and holds to high precision.[55] The Sagnac effect can be set in analogy with the Aharonov–Bohm effect,[56] through the analogy between the Coriolis force in a rotating frame and the Lorentz force from a magnetic field,[57] or equivalently the Larmor relationship. It can also be regarded as one optical manifestation of the Berry phase[58,11] and (hence or otherwise) as a consequence of time reversal violation.[59] It can be regarded as a prototype of the need for an anholonomic coordinate system, in which clocks slowly transported around different paths do not agree when next coinciding; it can raise questions on the relation between various historical concepts of time.[60] In addition, the rich set of theoretical connections possessed by the Sagnac effect has further potential to contribute to the extended philosophical debate on the nature of space, especially given the important role the absolute nature of rotation has played in these discussions.[61]

On a related topic, the role of moving and accelerated dispersive media in the beam path has been the focus of some theoretical discussion[46] and also of some remarkable and increasingly accurate experiments over many years in ring interferometry.[3,47]

III. RING LASERS

Conversion of a phase shift to a frequency shift greatly enhances the detectability of the effect for optical rings.[14] While this is possible in principle with passive interferometers if the resonator modes are beaten against those of an external cavity,[62,63] mechanical constraints on the matching procedures for the necessary injection are increasingly stringent and the complexity of the device is markedly increased. The advent of the laser led quickly to a more direct approach, in which the ring laser naturally displays a derivative of the Sagnac effect—the beating of counterpropagating modes at a frequency δf given by

$$\delta f = \frac{4\mathbf{\Omega}\cdot\mathbf{A}}{\lambda P}, \tag{3}$$

where P is the perimeter and λ the wavelength.[64] From Eqs. (1) and (3), the beat frequency δf is proportional to the fractional fringe shift $\Delta Z/Z = \delta\phi/2\pi$ in the corresponding passive interferometer, but the proportionality factor is large in electronic terms, being the free spectral range, that is, the frequency separation of longitudinal cavity modes $f_m = c/P$ so that $\delta f = f_m \Delta Z/Z$. The frequency difference δf can be thought of in the inertial frame as the result of a shift in the frequency of each mode as the corresponding wavelength stretches or shrinks to accommodate the new round-trip path length back to the same mirror; alternatively, one may think of the counterpropagating waves as forming a "necklace" or standing wave of light, past whose beads the mirrors and detectors move at the rate of δf beads per second.[65] The Sagnac effect was demonstrated for turntable experiments with greatly improved accuracy by Macek and Davies[66] using, like Lodge, a tabletop experiment, and indeed again an area of a square meter.

The history of the subsequent enormous development of this system for inertial guidance is fascinating,[3,9,12,14] although still obscured by commercial and military secrecy. One key result has been the vast improvement in mirror quality, "six-9's quality" (99.9999% reflectors) being now achieved. An example of the commercial pressures is given in the award by a USA jury in 1993 to Litton Corporation of US$1.2 billion in damages in its suit against Honeywell (who provide the commercial airline market with ring laser-based inertial guidance systems) in connection with the ion-beam mirror coating technology developed by a Litton licensee, Ojai Research.[68] Ring laser-based guidance systems are being developed in Japan as the basis of an automobile navigation system of the future, with the intention of making road maps obsolete.[69] Curiously, Sagnac himself had anticipated a not dissimilar use of three mutually perpendicular interferometers. He postulated in 1914[2] the use of three such rings, with areas of tens of square meters, in order to measure the roll, pitch, and yaw of ships. Contrary to the supposed custom in research, the area of ring laser performance has already proved its commercial usefulness; it is their scientific potential which has been neglected.

It has taken almost the full 100 years since Lodge and Larmor first discussed the matter for the Earth rotation effect to be clearly visible in tabletop optical experiments. The effect of Earth rotation on small to medium ring laser systems has been routine if undocumented (as unremarkable) in the aviation gyro industry for one and a half decades,[14] and has been explicitly if incidentally noted as a bias in a variety of ring laser setups.[70,49,67]

Fiber optic gyros have proved useful in a very wide variety of fields, such as oil prospecting. The Sagnac signal generated by the Earth rotation is sensitive to the orientation of the device, and if the orientation is defined by the ring laser being totally embedded in an oil well drill bit, the alignment of exploratory bores can be monitored deep underground. Thanks to advanced technological tricks including dither, such small gyros monitor the projection of the Earth rotation to an accuracy of 0.01°/h, a fraction 7×10^{-4} of the Earth's rotation rate Ω_E.[71]

The effect of Earth rotation is now being closely studied in a ring laser system (Fig. 2) associated with the University of Canterbury, Christchurch, New Zealand, in collaboration with Oklahoma State University, Stillwater, OK.[72] This again has an area of the order of one square meter and so may be reckoned as a tabletop experiment, although in this case the tabletop is 30 m underground (Fig. 3; a graphic comment on the location is given by Silverman)[73] and requires an equivalent of Lodge's stone altar, in the shape of a cubic meter of concrete tied into the basaltic volcanic rock of Banks Peninsula (at a latitude of 43°34′ S) to help provide the necessary mechanical and thermal stability. In Fig. 2, four supermirrors with losses of order 8–14 ppm are mounted on superinvar holders (visible through the box tops) which rest on a Zerodur plate. This is supported by a granite block, itself mounted via worm-drive-adjustable metal supports on the concrete pier. Stainless steel boxes, open on the top and bottom, and Pyrex connecting tubes, all sealed against each other, the Zerodur, and the glass box lids with Viton O rings, enclose the HeNe gas. At the far side an axial coil is fed by radio frequency to excite a HeNe plasma. At the furthest corner the transmitted components of the countercirculating beams are

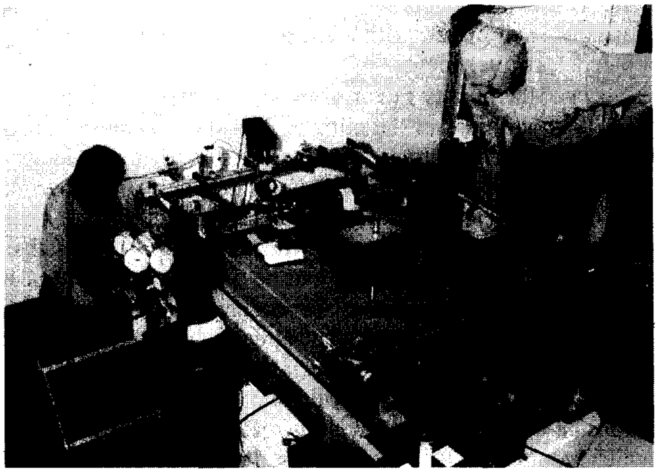

Fig. 2. The Canterbury ring laser system, with its specialist technicians Morrie Poulton and Clive Rowe. A description is in the text.

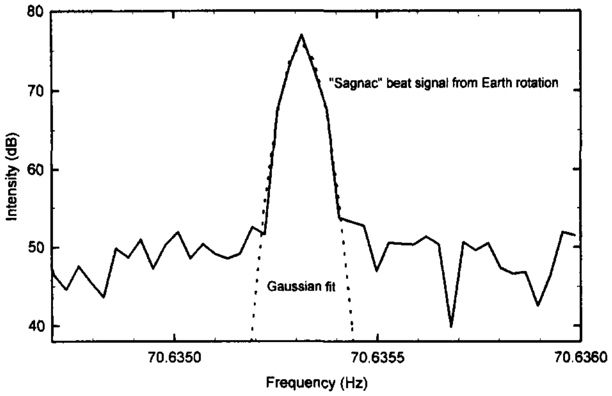

Fig. 4. Results of an 8 h run with the ring laser on 16 December 1993. The line has a full width at half-maximum power of 72 μHz, and its position can be determined to 5 μHz—a precision of 1 part in 10^{20} of the laser frequency (474 THz at 633.0 nm), and of 1 part in 10^7 of the Sagnac frequency.

brought out through a glass lid, then mixed at a beamsplitting prism, and the interferometric signal is detected by photomultiplier. Mirror alignment must be done with open boxes at atmospheric pressure, and to a precision of 10 μm and 20 arcsec; the green HeNe laser in the foreground assists in this. Gas- and vacuum-handling equipment is on the left.

In this ring laser the substantial improvement in mirror technology associated with the commercial development of ring-laser Sagnac-effect-based inertial guidance systems is exploited to permit monitoring of the Earth rotation signal at precisions of parts per million ($10^{-6}\ \Omega_E$). The Sagnac effect in this ring generates 68.95 Hz, highly amenable both to audio-frequency electronic processing and to direct monitoring by a speaker. A simple check that one is in the Southern Hemisphere is to press a corner of the table with the lightest of finger pressure: if the sense is clockwise, the pitch of the Sagnac signal audibly rises before it falls. More technically, this laser has a quality factor of better than 4×10^{10}, which may be compared with the present record[74] in atomic physics of 10^{13}, an area of 0.7547 m^2, and a perimeter of 3.47710 m.

A recent result from the Canterbury ring is shown in Fig. 4. The sensitivity of the device is adequate to determine the beat frequency with an accuracy of 5 μHz, the full width at half-maximum power of the line being 72 μHz. In this run, a small transverse magnetic field was applied to help stabilize the laser and has raised the frequency of the Earth-rotation-induced line slightly above the nominal Sagnac frequency of 68.95 Hz.

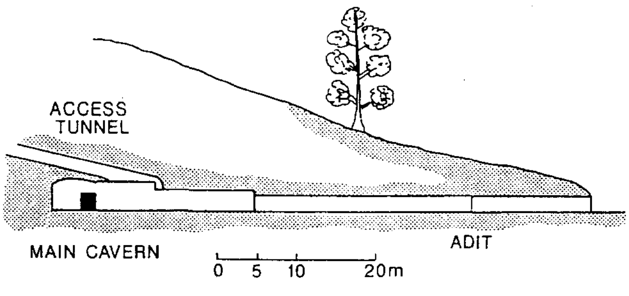

Fig. 3. Location of the Canterbury ring laser system. A war bunker built in case of Japanese invasion in a suburb of Christchurch, New Zealand has provided an ideal setting 30 m underground.

This is a remarkable result. It translates into a precision of 0.1 ppm of the Earth-rotation-induced beat frequency. It also translates into 1 part in 10^{20} of the HeNe laser frequency (474 THz). As far as we know, it is the most precise measurement of the frequency difference between two laser modes in any cavity, and by several orders of magnitude; in the state of the art for stabilized linear lasers, the frequency stability has not bettered tens of millihertz.[75] Finally, it represents a 12 order of magnitude improvement over the 1925 measurement of Michelson, Gale, and Pearson, with a ring whose area is less by a factor of 276 000. (Since submission of this manuscript, runs have been made permitting a resolution of 1 μHz or 2×10^{-21}.)[76]

At the present time, the accuracy of the Earth rotation measurement (ignoring this field dependence) is typically 0.1%, and is much less than its precision, on account of temperature-induced drifts, and also of pushing and pulling effects from mirror backscatter and plasma dispersion. However it is the precision rather than the accuracy which will dictate the limiting sensitivity of the instrument in many applications, such as the measurement of field-dependent effects.

This experiment itself has a variety of motivations.[72] It has demonstrated the feasibility of using larger precision ring lasers than had hitherto been thought possible (see Sec. IV). It has the potential to detect the rotational component of seismic events, something of a lack in conventional seismometry.[77] This capability is evident when the ring output is compared with a sensitive conventional (linear) seismometer, such as a Tokyo Sokushin SPC 35, at the same location; the instruments are complementary. It is difficult to correlate the observations of such a differential and probably highly local effect with major seismic events. It was intriguing that on 12:47, 17 January 1994 UT, the Canterbury ring sensed a local rotational seismic event of the order of microradians. Local diffraction in the initial shock wave from the 17 January 1994 Los Angeles earthquake (12:31, 17 January 1994 UT, 6.6 on the Richter scale) is a possible but unconfirmed explanation. Christchurch is a great circle distance of 11 100 km from Los Angeles; the *P* wave was detected at Kelburn, Wellington, New Zealand at 12:45, 17 January 1994 UT.[78] It is hoped to search for rotational effects associated with lunar Earth tides. The ring has already been used for a unique test of a preferred frame test theory in which subtle violations of local Lorentz invariance, not countenanced in PPN theories, and not detectable in linear (e.g., Michelson–Morley type) experiments, are contemplated.[17] Its precision is highly relevant to differential measurements of (for example) external electromagnetic field effects on the vacuum, the plasma, or any introduced gaseous or material sample. It could play a role, as have other ring laser experiments,[49] in searching for time reversal violation, which at either a local or global level is a more general definition of the Sagnac observable.[59]

IV. FUTURE RINGS: PRINCIPLES

A detailed study shows that a plane square ring is optimal. The use of one extra mirror over the basic triangle has advantages in reducing backscatter through the near-ideal incidence angle of 45°, in permitting alternative choices of polarization, and in maximizing the signal/loss ratio A/PN, where N is the number of mirrors and, as before, A is the area and P the perimeter.[72] In addition, the s reflectivity of a supermirror designed for normal incidence is in fact greater at 45° incidence than at either the design angle of 0° or the angle appropriate for a triangular ring (30°).

What is the practical limit on ring size? There has been considerable reluctance to move to rings with perimeters P greater than a few tens of centimeters. Indeed, an order-of-magnitude bound $P<P_0 \sim 60$ cm is given by Rodloff,[79] itself a quotation from a conference article.[80] Curiously, Simpson's argument is based partly on a geometrical fallacy. In a logarithmic plot of signal/quantum noise versus perimeter, the curve appears to have a knee at P_0, suggesting that greater rings do not achieve a worthwhile increase in sensitivity, especially in view of their (undisputed) increased sensitivity to mechanical and thermal instability. However the dependence of the signal/noise ratio on the perimeter is a simple power law, and as a consequence the position of this knee is a function of the scales used on the axes and can be varied at will. A more careful analysis which takes into account the need to employ the detailed shape of the gain curve to select the one permitted optical cavity mode shows that above a critical length, which for Ne at 300 K fortuitously turns out to be of the order of P_0, the signal/noise ratio *increases* as P^2. This is a powerful incentive to push for much larger rings. However the considerations of mechanical and thermal stability certainly have justified the cautions of Rodloff,[79] and have in the past imposed a practical upper limit on P of the order of P_0.

Recent progress in materials science has overcome this barrier to large rings. First, solid state research has provided materials whose thermal expansion coefficients are two orders of magnitude less than that of fused silica, and has also provided the technological expertise of being able to produce homogeneous large plates. For example, in Mainz, Germany, Schott is producing four plates of Zerodur each weighing 24 tons (metric) and with a diameter of 8.2 m for a next-generation telescope at the European Southern Observatory on Cerro Paranal, Chile. This has been described as "the most stupendous work in glass ever done."[81] In the United States of America, Corning has mastered the art of fusing large boules of ultralow expansion quartz together without loss of thermal stability. It is entirely reasonable to contemplate rings whose perimeters are defined by the neutral planes of such plates, with additional fine length control via a piezoelectric element.

Second, the quality factor of the cavity depends largely on the reflection losses of the mirrors. The shot (quantum) noise is proportional in turn to the inverse square of the quality factor Q. Thanks to the initiative of the optical gyroscope industry, multidielectric SiO_2–TiO_2 layer mirrors have been developed in the visible region with total losses of less than 10 ppm, and losses of 1 ppm can be anticipated in the near future. Nor is this the ultimate; arguments have been adduced, in analogy to what has already been achieved for optical fibers, that the true materials limit is nearer the parts per billion (ppb) level.[82] With such mirrors, cavity loss would be dominated by Rayleigh scattering in the laser gas, which would then set a practical limit on the quality factor of an active ring.

Third, the classical round-trip structure of the interferometers of Fizeau, Michelson, Harress, Sagnac, and Zeeman, etc. all employed purely optical means for extracting the signal. Later refinements, e.g., by Kennedy,[83] employed a quarter-wavelength shifter in a split optical field, and used electronics to compare intensities of the field sectors and so lead to accuracies of the order of 1/1000 fringe. As mentioned above, this can be improved even in a passive cavity if its resonance with an external cavity is properly investigated.[63,62] Nevertheless, historically the introduction of the ring laser made a qualitative change. This is partly because obtaining the equivalent resolution in a passive cavity is technically more demanding and so was delayed, and partly because an active ring laser is a pair of oscillators in the optical regime (the common red HeNe laser line is at 474 THz), so that the ring can now be integrated into a servosystem in a straightforward and well-defined manner by electronic control and processing systems. This aspect still awaits full development, and has major consequences for improving stability for big rings. Piezoelectric elements for path length control coupled with frequency references such as the abundant I_2 molecular resonances can stabilize the average of the mode frequencies in the cavity, making their splitting much less dependent on changes in absorption/gain and so dispersion with mode frequency drift. Similarly, precise control of the oscillation amplitude, electronic and computational (Fourier transform and signal analysis) noise reduction through filtering techniques, sideband analysis techniques, etc. (the output being highly monochromatic) all give good promise of maintaining and improving performance as rings are scaled up in size.

Fourth, a ring laser stands to benefit in principle from a range of techniques which perforate the "standard quantum limit" associated with quantum noise (or photon shot noise). With the current intense development in quantum optics, a variety of ambitious schemes has already been proposed that may realize the potential advantages. These include, e.g., quantum nondemolition measurements, the use of a nonlinear element in the cavity to induce squeezing in the observable of interest,[84] and the use of correlated excitation schemes for the two modes.[85] At the present time, the expected or achieved reductions in noise are not great, and in practice would be offset by the degradation of cavity quality if extra elements are required in the cavity; it is more useful to work within the standard quantum limit and lower its value by standard means, that is, by raising Q, and also P, given the constraint of single mode operation for each sense of rotation. However, attention is now focusing on the effects of injecting squeezed light into one or more ports of an optical ring cavity or the effects of correlated beam pumping. Such techniques, in avoiding intracavity elements, may prove beneficial in larger and high resolution rings.

The location of such big rings is critical. Buildings have substantial mechanical noise; even basements should be avoided, along with cultural (manmade) noise in cities and near traffic routes for example. Interactions between land and ocean—breakers on the beach—produce local microseismic fluctuations in the frequency range 0.1–1 Hz.[77] Avoiding such frequency bands may bring something of a renaissance for low-frequency electronics, as frequency or amplitude modulation techniques may then be optimally applied in the microhertz regime.

V. FUTURE RINGS: PRACTICAL

A serious attack on the present frontier has begun. A German collaboration, Forschungsgruppe Satellitengeodäsie for geodesical research via laser ranging and headed by Professor M. Schneider of Technische Universität München, in collaboration with Oklahoma State University, Stillwater and University of Canterbury, New Zealand, is designing an even larger ring laser—dubbed the "Grossring"—with an area of 16 m^2 and utilizing some state-of-the-art technology. Modest extrapolation from present results indicate that fluctuations in the rotation rate of the Earth (typically several milliseconds per day, i.e., at the level of 10^{-8} of the Earth rotation rate Ω_E) will then become clearly visible. This will give 13 orders of magnitude of improvement on the experiment of Sagnac for the measurement of an angular speed.

Such an instrument will give a completely localized alternative to the existing technique of intercontinental VLBI (very long baseline interferometry, based on radar measurements on astronomical objects) for measuring such rotations, especially on relatively short time scales (hours to days), since much faster data analysis will be possible; VLBI data processing takes 5 days. Such a system will fill a sizeable gap in our knowledge of the spectrum of fluctuations of the Earth rotation. The two major arms of this development are: the improvement in short-term noise by increasing the quality and size of the ring, and the increase in long-term stability to produce long time series in order to sense slow phenomena, kinematic or otherwise, in the Earth–Moon–Sun system. The limits on an independent Sagnac experiment will then no longer be associated with the limitations of the experimenter's apparatus, but will be determined by the stability of the Earth itself. It is the Earth noise—the local power spectral density of the mechanical movements of the Earth—which is the ultimate limit for large Earthbound Grossringe (big rings).

Such an instrument would represent a major and decisive step on the way towards realizing old proposals for measuring various effects[86–88] at the "general relativistic" level of $10^{-10}\Omega_E$ using ring lasers. This includes the ideas of Scully *et al.*[86] for an Earthbound ring either locked onto the stars to sense the Lense–Thirring frame dragging from Earth rotation, or alternatively, if rotating with the Earth, and at a similar level of precision, to pin down more precisely than the available (astrometric) experiments the preferred frame parameter α of the PPN (parametrized post-Newtonian, local Lorentz-, and metric-preserving) alternative family of theories of gravity. An orbiting ring laser[87] has been proposed for gravitational wave detection, although a figure-8 ring is arguably more suitable.

All these rings are still of substantially smaller area than any of those contemplated by Michelson in 1904 or built by him in 1925. Since the possibility of a dragging effect was anticipated by Lodge, Larmor, Michelson, and Sagnac, it might be said that after a century of development we are closing the circle in the history of the rotating interferometer as a test of relativity. However, the theoretical motivations for these ring interferometer/laser experiments have proliferated, altering the original rationale for the experiment almost beyond recognition. The experiment of Sagnac is possibly unique in the connection it gives between conceptual simplicity of description on the one hand and, on the other, the extraordinarily wide variety of theoretical frameworks and expectations accorded to the experimental results at differing levels of precision. Even in this paper it has afforded what must nowadays be something of a rarity: the collaboration of a philosopher and historian, an engineer and a physicist in the true spirit of Natural Philosophy.

ACKNOWLEDGMENTS

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APPENDIX: THE LARMOR–LODGE DISCUSSION

It is helpful first to give as a perspective the account Lodge gives in his autobiography[27] of the history of the relevant period and experiments. In this excerpt only, square brackets denote our comments. Lodge described his work on the "whirling machine" as follows.

> ⋯ the most important series of experiments in my life, which took many years to carry out ⋯ There was a controversy at the time as to whether the velocity of light as determined on the earth's surface was in any way affected by the motion of the earth; or, since no one doubted that the ether was the vehicle conveying light, it might be expressed as whether the ether was carried along by the earth at all ⋯ Some people suggested that the Michelson [–Morley] experiment proved that the ether near the earth was carried along with it ⋯ In opposition to this view was my experiment showing that a rapidly moving body of small mass did not drag the ether with it in the least ⋯ Fizeau had shown that when light entered transparent matter it certainly was affected by the motion ⋯ No reconciliation seemed to be forthcoming. ⋯ Fitzgerald ⋯ said ⋯ 'the stone [defining Michelson and Morley's mirror positions] would have to shorten in the direction of motion ⋯ I believe this distortion occurs with all moving bodies' ⋯ this whole hypothesis was immediately afterwards illuminated and consolidated by Lorentz ⋯ I still ⋯ cling to the idea that the Fitzgerald contraction is a reality ⋯

The question of the role of the Earth's rotation was evidently raised by Lodge to Larmor. We have not been able to trace the entire correspondence. From what we have (see below), the ensuing correspondence went through several false trails.[89] On 28 January 1897, Larmor wrote to Lodge:

> Dear Lodge,
>
> It is suggested that you are going to reverse the rotation of the earth in order to get an interference effect round your circuit. But I think it is extremely doubtful whether you will get one. I think it is demonstrable ⋯ that if a material system is in *uniform rotation* through the stationary aether, there should be no interference effect of the first order of small quantities between the halves of the divided beams unless the circuit passes round the axis of rotation,—in your case round the North Pole ⋯
>
> P.S. But possibly you expect that the aether is not stationary but to some extent participates in the earth's rotation ⋯ [which] will give a first order effect. Thus time of transit
>
> $$=\int \frac{ds}{c+\omega r\cos\phi}=\int \frac{ds}{c}\left(1-\frac{\omega}{c}r\cos\phi\right)$$
>
> $$=\int \frac{ds}{c}-\frac{\omega}{c}\int r^2 d\theta=\int \frac{ds}{c}-\frac{2\omega A}{c^2},$$
>
> where A is the area of the projection of the circuit on a plane at right angles to the Earth's axis: this gives about a wavelength $(4\omega A/c^2)$ retardation for A equal to a square kilometer, if the aether were carried along bodily.

Following this is a paragraph which was later crossed out:

> But you may not require to reverse the earth's rotation to make an experiment. There will also be the centrifugal forces of the rotation on the aether ⋯ this result would be different for a beam polarized in a plane through the earth's axis and for one polarized in the perpendicular plane ⋯

The prediction in the first paragraph of the above letter was repeated in a letter from Larmor of 31 January 1897, with the caveat,

> I am not *very sure* that my method is legitimate but I see no flaw as yet: if true the result is striking. I dare say your instinct is a safer guide ⋯

By the way, the possibility of a coupling between rotation of the frame and polarizations of the beams has resurfaced recently.[88]

We now give parts of a letter from Lodge to Larmor dated 3 February 1897. Annotations by Larmor on this letter and the one to follow are noted in italics and square brackets:

> Dear Larmor,
>
> ⋯ Your calculation
>
> $$\int \frac{ds}{c+\omega r\cos\phi}=\int \frac{ds}{c}-\frac{2\omega A}{c^2}$$
>
> [*ω is ang. vel. of aether relative to moving earth*] assuming the ether to be revolving with the earth also *assures* that the observer etc. are stationary otherwise everything would be stagnant together, without relative motion, and might as well be at rest. [*Yes, but I thought your idea was that the aether would not be carried as much as the observer, so that there would be a differential motion between them. Otherwise there is nothing in it.*] I agree that if the ether is carried round & observer fixed you get your effect, & of course that is my disk experiment. But I also argue that if ether is stationary & observer etc. in rotation, there must also be an equal effect. [*This depends on whether the source of light is moving with the observer or his apparatus?*] (though it is only of an aberrational i.e., subjective or apparent kind). [*I rather think not* ⋯] Hence I say that on the earth an effect will exist *unless* the ether moves with the earth. I am surprised that you attribute special virtue to the earth's axis, making it a singular point. I should have thought that there was a rotation $\omega\sin\lambda$ [*velocity?*] about any axis & that locality didn't matter ⋯ [*Yes; I had noticed this.*] You don't attribute vorticity properties to the earth rotation? [*Yes. In uniform rotation of solid $u=\omega y$, $v=\omega x$, therefore vorticity$=\frac{1}{2}(dv/dx-du/dy)=\omega$; vorticity only means rotary motion*] I think your $4\pi C$ change of potential sort of business in last letter all wrong! [*I can't remember anything like that at all.*]

There is understandably some muddled thinking here still, particularly on Larmor's part, for example the supposed requirement for the circuit to enclose the polar axis, and the concern over the speed of the light source. However, Larmor and Lodge are each intending to converge on the situation with relative rotation of the aether and the observer with the interferometer.

On 6 February 1897, Lodge wrote again:

> Dear Larmor,
>
> ⋯ Certainly my idea is that the ether will not be carried on so much as the observer, in fact not at all—even by the earth. But the point is that one could thus discriminate (if the earth experiment were practicable) between stationary and carried ether, because if the ether is stationary we get the $2\omega A/c^2$ effect [*due to the observers etc. motion*] and if the ether is moving with the earth at the same speed we get 0 (or anything in between of course). But then you come in and say No. You won't get the $2\omega A/c^2$ effect unless you go to the poles and string your circuit round that singular point; & this is what I meant by your "$4\pi C$ change of potential sort of business." $2\pi\alpha$ I see I ought to have called it, the change in time reckoning appropriate to circumnavigating the earth. You don't change the day unless you encircle the pole ⋯ You would admit that if in my machine I whirled observer & everything (except the ether of course) I should get an effect:—no you might not, you don't like the source moving. It's as bad as the beastly old aberration problems over again and wants thinking out ⋯ I'll write again ⋯ & I will then return your nasty calculation slip ⋯

Hunt's[29] complementary account of the Larmor–Lodge correspondence illuminates for example this mention of aberration. After some intermediate correspondence, Larmor replied on 6 April 1897:

> Dear Lodge,
>
> I am pretty certain that my statement that you quote was wrong, and I believe I see where the fallacy lay; the argument only applied in the ordinary case of uniform translations ⋯ I think your view is right as regards the effect of the aether rotating partly with the earth: namely time of a revolution
>
> $$=\int \frac{ds}{V+\omega r\sin\psi}=\frac{path}{V}-\frac{2\omega\cdot area}{V^2}.$$
>
> Thus the difference of the times right and left is $2\omega\cdot area/V^2$, provided those paths are the same. The latter is the *real question*: they seem certain to be the same when

> the mirrors are arranged as parallel pairs and the rays then strike each such pair are parallel, for then the rays reflected from them are also parallel.
>
> I dont quite see what you prove by whirling *yourself* around as you suggest. It appears to me that you get an effect only because you are traveling to meet one beam and at the same time are running away from the other one. You will have also the effect of convection by the Earth⋯ coming in as a second order term: but then that is far beyond your limitations.
>
> You can conceivably tell which of the interfering beams travels round with the Earth by means of the opposite polarizations impressed on the two when they are divided ⋯

At this stage there is still a measure of confusion or inaccuracy in Larmor's thinking—the loss of the factor of 2 when comparing "right" and "left" (clockwise and anticlockwise) beams (Michelson had a similar flaw in his 1897 paper), the concern over the identity of the beam paths, the supposed commitment of each beam to a unique polarization. However it is certain that Lodge has been motivated by an interest in the induction of a Sagnac effect by Earth rotation, that he clearly expects a Sagnac effect, and that Larmor despite some unsupportable misgivings has contributed to the discussion the bones of a correct (ether–theoretic) derivation of Eq. (1).

The matter is briefly discussed in Lodge's 1897 Philos. Trans. paper; the latter was submitted on 19 January (we note in passing that A. Schuster refereed the 1893 paper),[29] and read at a meeting of the Royal Society on 4 March 1897.[90] Lodge records here (p. 151) a statement, clearly arising from an early stage of the discussion, saying:

> Now, by staking out mirrors at the corners of a field, it is arithmetically quite possible to arrange for a perceptible shift of the bands due to the rotation of the earth, if it carries ether round with it; but it does not seem possible to experimentally observe that shift, unless some method could be devised of making the observer and his apparatus independent of the rotation.

Lodge also considered in the same context the converse case in which the observer and apparatus, but not the ether, rotated:

> Hence if, instead of spinning only the disks, the whole apparatus, lantern, optical frame, telescope, observer and all were mounted on a turntable and caused to rotate, a reversible shift of the bands should be seen ⋯ my present optical apparatus mounted on a turntable revolving 4 times a minute should show something, viz. 1/100th band shift each way ⋯ If the ether is stationary near the earth, that is, if it be neither carried round nor along by that body, then a single interference square, 1 kilometer in the side, would show a shift of rather more than one band width, due to the earth's rotation in these latitudes; see p. 772, 'Philos. Trans.' 1893. But as the effect depends on the area of the square, a size of frame capable of mechanical inversion is altogether too small; there may however, be some indirect ingenious way of virtually accomplishing a reversal of rotation—something for instance based on an interchange of source and eye and if so it would constitute the easiest plan of examining into the question of terrestrial ether drift.

Hence Lodge deserves credit for the first proposal of a square kilometer interferometer to measure the Earth's rotation. Indeed Lodge had already wrestled with Telegdi's "devil." The published report which followed Lodge's reading of his paper brings this out clearly:[90]

> ⋯ by rotating the whole apparatus and observer ⋯ at a very moderate speed, a shift of the bands should be seen; and even that the earth's rotation would with a large enough frame produce an effect, which latter, however, it appears difficult or impossible to observe not on account of its smallness, but on account of its constancy.

In his 1897 paper, Lodge also gives a reference to his earlier derivation of a Sagnac effect, and so for such practical applications as his estimate of the necessary size of the interferometer needed for the Earth's rotation to be detectable, as well as the angular speed necessary for Lodge's own tabletop device to register the Sagnac effect. Lodge's 1893 derivation, to which he later refers as mentioned above, is a simple calculation of "ether drag" effects for a light beam traveling around a square. With the obvious reinterpretation implied by Lodge in his 1897 reference, this 1893 calculation is perfectly consistent with that of Sagnac. The above-quoted correspondence with Larmor shows that this quantitative expression was written by Larmor as early as 1897 in a relatively modern form, and as such was known also to Lodge in presenting his 1897 paper.

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[1] G. Sagnac, "L'éther lumineux démontré par l'effet du vent relatif d'éther dans un interféromètre en rotation uniforme (The luminiferous ether demonstrated by the effect of the relative motion of the ether in an interferometer in uniform rotation)," C. R. Acad. Sci. (Paris) **157**, 708–710 (1913). This is the first reference recording a successful observation of the effect. It was followed by "Sur la preuve de la réalité de l'éther lumineux par l'expérience de l'interférographe tournant," *ibid.* **157**, 1410–1413 (1913). We quote from an English translation by R. Hazelett in the (otherwise not recommended) work *The Einstein Myth and the Ives papers*, edited by D. Turner and R. Hazelett (Devin–Adair, Old Greenwich, 1979). This records four observations: 0.026 fringe (later adjusted to 0.0264 fringe) at 0.86 Hz, 0.070 fringe at 1.88 Hz, 0.072 fringe at 2.21 Hz, and 0.077 fringe at 2.35 Hz. A straight-line fit to these data has an rms error equivalent to 0.73 rad/s.

[2] Sagnac refers back to his paper in Comptes Rendus **141**, 1220 (1905) and also several papers in 1901. He gives a full account in G. Sagnac, "Effet tourbillonnaire optique. La circulation de l'éther lumineux dans un interférographe tournant," J. Phys. Radium Ser. 5 **4**, 177–195 (1914).

[3] E. J. Post, "Sagnac effect," Rev. Mod. Phys. **39**, 475–493 (1967). This major review includes many comments which we do not attempt to cover.

[4] D. Dieks, "Physics and geometry: The beginnings of relativity theory," *Proceedings of the Eighth General Conference of the European Physical Society (EPS-8, Trends in Physics)*, edited by J. Kaczér (Prometheus, Prague, 1991), Part III, pp. 969–982. Dieks includes some historical comments including an account of Einstein's and Langevin's interests.

[5] A. A. Michelson, "Relative motion of earth and aether," Philos. Mag. **8**, 716–719 (1904).

[6] F. Harress, thesis, Jena (unpublished). A full account is in O. Knopf, "1. Die versuche von F. Harress über die geschwindigkeit des lichtes in bewegten körpern," Ann. Phys. Vierte Folge **62**, 389–447 (1920). M. von Laue, *ibid.*, pp. 448–463, discusses Harress's experiment and concludes that, in first order, "classical" descriptions of rotations are identical to general-relativistic treatments. See also B. Pogany, "1. Über die wiederholung des Harress–Sagnacschen versuches," Ann. Physik **80**, 217–231 (1926).

[7] We are indebted in part to Dr. W. H. Steel for so amplifying the comment by Post (1967).

[8] P. Zeeman, W. de Groot, A. Snethlage, and G. C. Diebetz, "The propagation of light in moving, transparent solid substances," Proc. R. Acad. Sci. (Amsterdam) **22**, 1402–1411 (1921), and references therein.

[9] C. V. Heer, "History of the laser gyro," Proc. SPIE **487**, 2–12 (1984).

[10] W. Schleich, P. Dobiasch, V. E. Sanders, and M. O. Scully, "Nonequilibrium statistical physics in a dithered ring laser gyroscope, or quantum noise in pure and applied physics," in Frontiers of nonequilibrium statistical physics, edited by G. T. Moore and M. O. Scully [NATO Adv. Study Inst. Ser. B: Physics **135**, 385–408 (1984)].

[11] F. Hasselbach and M. Nicklaus, "Sagnac experiment with electrons: Observation of the rotational phase shift of electron waves in vacuum," Phys. Rev. A **48**, 143–151 (1993).

[12] W. W. Chow, J. Gea-Banacloche, L. M. Pedrotti, V. E. Sanders. W. Schleich, and M. O. Scully, "The ring laser gyro," Rev. Mod. Phys. **57**, 61–104 (1985).

[13] D. MacKenzie, "From the luminiferous ether to the Boeing 757: A history of the laser gyroscope," Technol. Culture **34**, 475–515 (1993).

[14] G. E. Stedman, "Ring interferometry tests of classical and quantum gravity," Contemp. Phys. **26**, 311–32 (1985); G. E. Stedman, "Ring interferometric tests of nonclassical gravitational effects," in *Quantum Optics IV*, Proceedings of the 4th International Symposium, 10–15 February 1986, edited by J. D. Harvey and D. F. Walls (Springer, Berlin, 1986), pp. 259–266.

[15] R. Anderson and G. E. Stedman, "Distance and the conventionality of simultaneity," Found. Phys. Lett. **5**, 199–220 (1992); "Spatial measures in special relativity do not empirically determine simultaneity relations: A reply to Coleman and Korte," *ibid.* **7**, 273–283 (1994).

[16] I. Vetharaniam and G. E. Stedman, "Significance of precision tests of special relativity," Phys. Lett. A **183**, 349–354 (1993).

[17] I. Vetharaniam and G. E. Stedman, "Accelerated observers: Synchronization and tests of local Lorentz invariance," Class. Q. Gravity **11**, 1069–1082 (1994).

[18] A. A. Michelson, H. G. Gale, and F. Pearson, "The effect of the earth's rotation on the velocity of light," Astrophys. J. **61**, 137–145 (1925).

[19] R. S. Shankland, "Michelson and his interferometer," Phys. Today **27**, 36–43 (April 1974).

[20] V. L. Telegdi, "Mind over matter: The intellectual content of experimental physics," CERN Report No. 90-09, Geneva, November 1990. Since Telegdi's description is not available in the open literature, we venture to quote one key point: "Michelson ··· could obviously not stop the earth's rotation. How did he beat the devil? ··· The interferometer had a long circuit ADEF and a short circuit ADCB ··· How could a relative shift due to misalignment of the mirrors be excluded? The argument goes as follows. Either circuit produces *two* images of the source, namely a direct and a reflected one (independently of interference or rotation). In the middle between these two images is the interference pattern, with the zero-order fringe in the center. The central fringes of the short circuit and those of the long circuit would be halfway between the direct and reflected images if there were no effect due to the earth's rotation ··· the observing telescope was focused on the images of the source and the apparent relative displacement of the central fringes corrected by an amount equal to the difference in the mean positions of the two images of the two circuits." It is also interesting to note that in the Michelson–Gale experiment, while the average of the 269 measured fringe displacements is 0.229 of a fringe, the rms deviation of one measurement from the average is as much as 0.103 fringe. The error of the average is then statistically reduced to 0.0064 of a fringe. Michelson *et al.* give as their final result 0.230±0.005 fringes.

[21] L. Silberstein, "Propagation of light in rotating systems," J. Opt. Soc. Am. **5**, 291–307 (1921).

[22] O. J. Lodge, "Aberration problems—a discussion concerning the motion of the ether near the earth, and concerning the connection between ether and gross matter; with some new experiments," Philos. Trans. R. Soc. London Ser. A **184**, 727–807 (1893); "Experiments on the absence of mechanical connexion between ether and matter," *ibid.* **189**, 149–165 (1897).

[23] J. R. Wilkinson, "Ring lasers," Prog. Quantum Electron. **11**, 1–103 (1987).

[24] H. G. Gale, "Albert A. Michelson," Astrophys. J. **74**, 1–9 (1931), in discussing the 1925 experiment with Michelson, mentions that "the same experiment had been suggested by Sir Oliver Lodge."

[25] J. Larmor, letter to the Royal Society, 16 January 1897, Royal Soc. MS RR.13.220.

[26] Figure 1 and the quotations in the Appendix are reproduced by kind permission of the Librarian of University College, London and the President and Council of the Royal Society of London.

[27] O. J. Lodge, *Past Years: An Autobiography* (Camelot, London, 1931), Chap. XV.

[28] P. Rowlands, *Oliver Lodge and the Liverpool Physical Society* (Liverpool University Press, Liverpool, 1990), p. 68. He gives for example an excerpt from the Liverpool University College magazine to the effect that: "··· the ether machine ··· (by) virtue of its size and mysterious appearance (commanded) universal respect (at University College) ···."

[29] B. J. Hunt, "Experimenting on the ether: Oliver J. Lodge and the great whirling machine," Hist. Studies Phys. Biol. Sci. **16**, 111–134 (1986). Professor Hunt has commented on a draft of this paper: "The closest thing to a 'smoking gun' I've seen linking Michelson to Lodge's work... is a mention in Lodge's letter to Larmor of 19 October 1897 that 'I saw Michelson in America' (presumably at the Toronto meeting of the British Association for the Advancement of Science, 19–25 August 1897, which both attended) 'and talked with him about methods for detecting the Zeeman effect.' They may well have talked about interferometer and 'Sagnac-type' problems then."

[30] R. S. Shankland, "Michelson in Potsdam," in Z. Geschichte Naturwiss. Tech. Medizin **19**, 27–30 (1982).

[31] H. B. Lemon, "Albert Abraham Michelson: The man and the science," Am. Phys. Teach. **4**, 1–11 (1936). Lemon includes the statement: "At the breaking-up of a luncheon meeting during which [Michelson's] assent to the project had been obtained, he remarked in conclusion, "Well, gentlemen, we will undertake this, although my conviction is strong that we shall prove only that the earth rotates on its axis, a conclusion which I think we may be said to be sure of already.' " However, as an experiment in optics, it must have had its attractions; Michelson's own collaborator Gale (Ref. 24) described the 1925 experiment as "an experiment which Professor Michelson had wished to try for years... ."

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[78] This distance assumes Northridge Los Angeles, USA, to be at 34°14′N, 118°33′W; and the Cashmere cavern, Christchurch New Zealand at 43°35′S, 172°38′E. The Northridge-Cashmere course and distance are 223°, 11105 km; the Kelburn–Cashmere figures are 214°, 309 km. For our comparison with the Kelburn data, we acknowledge gratefully the help of Dr. T. H. Webb of IGNS, Wellington, New Zealand.

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[90] An abstract of Lodge's paper is given with the report of his reading of his 1897 paper in Proc. R. Soc. London **61**, 31–32 (1897). The abstract was also reproduced in Nature **55**, 477 (1897).

KINETIC THEORY

On one occasion [Maxwell] was wedged in a crowd attempting to escape from the lecture theatre of the Royal Institution, when he was perceived by Faraday, who...accosted him in this wise—"Ho, Maxwell, cannot you get out? If any man can find his way through a crowd it should be you."

Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (MacMillan and Co., London, 1882), p. 319.