Dispersion effects in frequency windows of millimeter range radiowaves

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ABSTRACT

Measurements of wide band signal propagation peculiarities have been carried out in 37 GHz range under different season and meteorologic conditions on 13 km long direct visibility path over rugged country near Kharkov (Ukraine). Dispersion effects conditioned by direct and indirect meteorologic and season factors have been discovered and measured. A method which allows measurements of difference-phase shifts in received signals has been developed. Quantitative evaluation of atmospheric communication channel coherence band variation has been carried out.

INTRODUCTION

In development of modern radio engineering systems and radiolocation wide band signals with band width of 1 GHz and more may be used[1] In such systems, along with waveguiding and cable signal propagation lines, open atmospheric lines in which wide band signal propagates in turbulent stmosphere over the rough division surface are also used. In such lines signal power losses may occur, and also its coherence losses, which lead to limitations of response, accuracy and resolution of radio engineering systems.

Additional limitations of coherence band may arise because of the dispersion in communication channel (dependence of the refraction factor n from the frequency ω). Dispersion characteristics of the open communication lines operating at frequencies corresponding to atmospheric gases molecular absorption bands[2,3] are studied quite well. Some peculiarities connected with hydrometeors dispersion characteristics are also considered[4,5] As a rule, available results show weak frequency dependence of the value n in the atmosphere "frequency windows"[6].

The aim of the work is development of the phase invariant method applied to the problem of wide band signals of millimeter range propagation in real media and measurements of the coherence band limitations arising from meteorological and season factors.

1.MEASUREMENT METHOD AND EQUIPMENT

The developed method is based on the measurement of difference-phase characteristics in discrete spectrum of wide band signal[7,8,9]. A spectrum of such a signal may be formed by frequency multiplication or

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by carrier frequency ω_0 amplitude or angular modulation. An important feature of the signal is a strict link between single discrete components of its spectrum. The essence of the method is the following. The sensing modulated $\mathcal{E}$ signal with the carrier frequency ω_0 and with frequencies of the lower and upper side components $\omega_1=\omega_0-\Omega$ and ω_1 $\omega_2=\omega_0+\Omega$, respectively,(Ω is modulation frequency) is radiated into the channel under investigation. While propagating each $\mathcal{E}$ signal spectrum component receives the following phase increment

$$\varphi_i = \omega_i \, n(\omega_i) z c^{-1}, \tag{1}$$

which are proportional to both their frequencies ω_i , a radio channel length z , and propagation medium dispersion characteristics $n(\omega_i)$. It follows from(1)that under the condition of radiowaves propagation in dispersion free medium ($n(\omega)=$ const) the dependence $\varphi(\omega)$ is frequency linear function, and in dispersion media ($n(\omega \neq$ const) it is frequency non-linear function. Examples of such dependences and spectrum $S(\omega)$ shape of the signal $\mathcal{E}$ are shown in Fig.1. It is obvious that segments from Y axis corresponding to frequency segments from X axis (that is ensured by the modulation law) are equal to $\varphi_0-\varphi_1$ and $\varphi_2-\varphi_0$. In dispersion free medium they are equal to each other, but in dispersion media they are not. Thus the measure of unequality of the segments is dispersion measure in radiowaves propagation channel which may be written in the form of difference of the segments

$$\Delta\varphi = (\varphi_0-\varphi_1)-(\varphi_2-\varphi_0) = 2\varphi_0-\varphi_1+\varphi_2$$

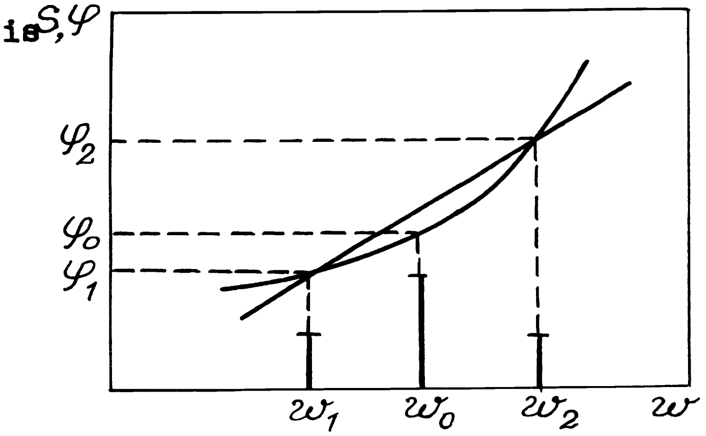

Fig.1.Examples of phase-frequency characteristics of communication lines and sensing signal spectrum.

In [8,9] such combination of spectrum components phases of modulated signal was called "phase invariant" because it does not vary in space and time, provided that the signal propagates in dispersion free medium. In case of dispersion medium $\Delta\varphi \neq$ const and $\Delta\varphi$ depend on dispersion value and z , and sign of $\Delta\varphi$ is determined by the law (character) of dispersion value variation (normal and abnormal). To measure the value of $\Delta\varphi$ at the receiving end of the radiowaves propagation channel the carrier oscillation of the received sensing signal $\mathcal{E}$ is separately multiplied with signals of each side frequency. Further on phase shift between the results of multiplication having difference frequencies is measured. This is the value of phase invariant $\Delta\varphi$.

To carry out the investigation transmitting and receiving equipment applying measurement method in 8 mm radiowave range has been developed and produced. Transmitting device carrier frequency is 37 GHz, modulation frequency is 0.5 GHz. Transmitting device output power is 70 mW.

To reduce equipment error during the measurements a special attention has been payed to the tuning, correction and calibration of phase-frequency and phase-amplitude characteristics of the measuring equipment units. Transmitting device and main units of receiving device have been thermostated. During the measurements the equipment was calibrated by the test signal with controlled parameters analogous to the sensing signal spectrum. The resulting root-mean-square equipment error of the value $\Delta\varphi$ measurements has not exceed 0.5°. The receiving device antenna was mounted at an altitude of 30 m above the earth surface, and the transmitting device antenna - at an altitude of 12 m. Both antennae were identical with the parabolic reflectors diameter of 1.1 m. The measurement equipment included meteorological equipment and rain intensity measuring device.

Experimental communication line has been selected in terms of the following conditions: sufficient extent modelling real lines, absence of considerable reflections from the earth surface, possibility of direct radio visibility under any meteorological conditions. The communication line with the length of 13 km over the hilly terrain has been chosen. The average altitude of the radiowaves propagation channel was 50 m over the earth surface. Measurements of the vertical field structure carried out under different meteorological conditions in location of receiving device and calculation of the field structure made in approximation of the wave diffraction in the zone on tops of the hills have shown that results of the experiment and the calculation agree well. That allow to estimate possible diffraction errors of the value $\Delta\varphi$ measurement with the change of refraction conditions. Calculations showed that the errors did not exceed values of $\pm 1^{\circ}$.

After propagation in the communication line the radiated sensing signal was received by the receiving device, in which it was processed according to selected measuring method. Simultaneously the intensity of spectrum side components J_1 and J_2 of the received signal spectrum was measured. The measured values of $\Delta\varphi$, J_1 , and J_2 were directed to the recorder. Calibration of the equipment and measurement of meteorological elements were carried out not less than one time per an hour of observations. The rain intensity was estimated by means of a cup-shaped rain gauge and by values of signal attenuation in the precipitations. The experiments were carried out for one year under different meteorological conditions: clear weather, rain, snow, etc. Clear weather conditions were considered the cases when no hydrometeors fall-out was observed in the radiowaves propagation channel during the experiment. Measurements results obtained as a rule during one day (24 hours) when one or another atmospheric phenomenon was observed were considered one experiment. The measurement results procession was carried out to obtain the following temporal characteristics:

$\Delta\varphi_d(t)$ is daily variation of the average phase invariant value,

$\Delta\varphi_{ds}(t)$ is season average daily variation of the phase invariant value.

Dependences of $\Delta\varphi_d(t)$ obtained according to the averaging results of 5 minute intervals of $\Delta\varphi(t)$ realizations. Dependences $\Delta\varphi_d(t)$ were grouped according to the season and for each of them the dependence

$\Delta\varphi_{ds}(t)$ was calculated. The calculations were conducted according to the following algorithm

$$\Delta\varphi_{ds}(t) = \frac{1}{m}\sum_{j=1}^{m} \Delta\varphi_{jd}(t)$$

where m is a number of experiments during the season, t is time.

Total number of experiments is 237. Total time of the continuous measurements of $\Delta\varphi$ values is 2186 hours. Conducted experimental investigations have revealed differences in influence of various atmospheric phenomena on phase invariant value and variability.

2. MEASUREMENTS RESULTS

In clear weather in different year seasons the temporal realizations of $\Delta\varphi(t)$ presented weakly fluctuating dependences with smooth average diurnal variation. The values of $\Delta\varphi$ measured in summer were as a rule negative, while measured in winter they were positive. In spring and autumn the change of the sign of measured value was observed. Statistic processing of the observation results has shown availability of regular variations of $\Delta\varphi$ values. Dependences calculated for the day time are presented in Fig.2. Dependences corresponding to winter, spring, autumn and summer seasons are marked in the figure by digits 1,2,3 and 4. The values of confidence intervals determined for the probability estimation of 0.95 are marked by vertical strokes. The characteristic feature of $\Delta\varphi_{ds}(t)$ variations is presence of extrema in the interval between 2 p.m. and 4 p.m.

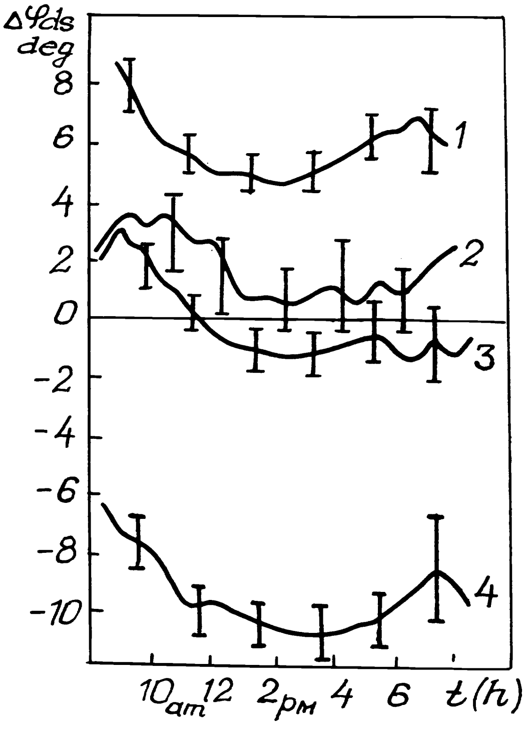

Fig.2. Average seasonal diurnal measurements of phase invariant.

The experimental investigations allowed to reveal diurnal and seasonal variation of the phase invariant values, which in terms of selected measuring method is a parameter characterizing dispersion value and variation law. The analysis of measurements results showed that such phenomena as dispersion in atmospheric gases, atmosphere turbulence, diffraction on the underlayer obstacles under conditions of variable refraction did not allow to obtain a satisfactory qualitative and quantitative explanation of the experimental results. Thus, it was experimentally estimated that in the atmosphere "frequency windows" in millimeter wave range the near-surface atmosphere layer showed the properties of a regular dispersion medium. The value and the variation law of the dispersion has diurnal and seasonal variation.

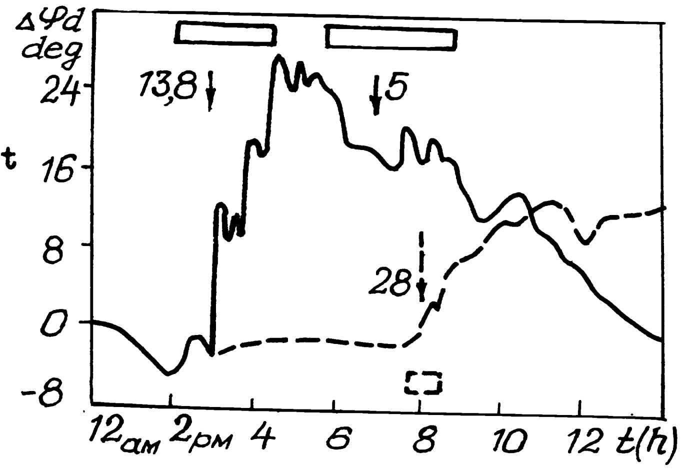

Fig.3. Measurement results of phase invariant during rain fall-out.

The rain fall-out during the warm season (summer and beginnning of the autumn) caused a considerable increase of the $\Delta\varphi$ values up to 20°...30°. Characteristic measurement results obtained under such conditions are presented in Fig.3. Time in hours is plotted on x axis. The measurement results in two different experiments are shown by solid and dotted lines respectively. The duration of rainfalls and their temporal position are marked by rectangles. Arrows indicate the instants of the strongest attenuation of the signal received, caused by rains. Figures by the arrows correspond to the attenuation values (in dB) measured at those instants. The characteristic feature of the data was a considerable up to 50 minutes, delay of the $\Delta\varphi$ value increase as to the beginnning of the rain. In case of "short" rain (Fig.2, dotted line) the increase of the $\Delta\varphi$ value was observed after it ceased. The decrease of the $\Delta\varphi$ value down to initial level was gradual and lasted for several hours. The experiments results showed that the presence of rain drops in radiowaves propagation channel was not the direct reason for the $\Delta\varphi$ value increase.

The measurements made during intensive long snowfalls showed that if the snowfalls were caused by the motion of a warm atmospheric front then diurnal $\Delta\varphi$ variations practically did not differ from the same dependence measured in dear winter weather (Fig.2, curve 1). Such experiments showed that the presence of snow flocs in the radiowaves propagation channel did not have strong affect on the $\Delta\varphi$ value typical for the winter season. But, provided that the snowfall was caused by the cold atmospheric front motion, a considerable, up to 30°, increase of the measured value was observed. The result of an experiment carried out under such conditions is given in Fig.4. The figure is accompanied by the results of synchronous air temperature measurements (Fig.4, dotted line). Snow falled continuously during the whole experiment (12 hours). Time intervals when snowfall was the most intensive are marked in the figure by rectangles. It is obvious that the beginning of the $\Delta\varphi$ value increase coincided the beginning of the air temperature decrease, which later falled down to -12°C.

The considered results of experimental investigations present typical time variations of phase invariant observed under different meteorological and season conditions. But data about extremum values of phase invariant observed during the experiments are also undoubtedly useful. Such results are not representative but they outline boundaries of the measured value and show the conditions in which they were observed. The result of the experiment in which maximum positive value $\Delta\varphi$ = 64° was observed is presented by the solid line in Fig.5. The result was obtained at the end of autumn when cold atmospheric front

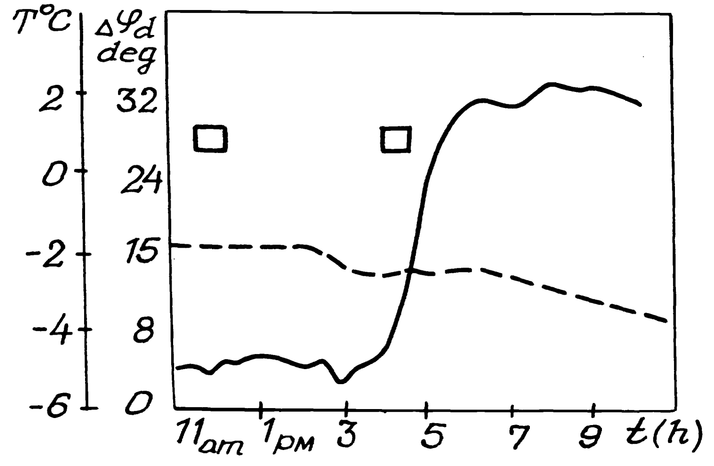

Fig.4.Measurement results of phase invariant while passing cold atmospheric front.

accompanied by rain and snow passed. In the same figure the result of the experiment in which maximum negative value of $\Delta\varphi = -24^{\circ}$ was observed is given by the dotted line. The experiment was carried out at the end of spring in clear cloudless days with steady hot weather. During the experiment at 3.20 p.m. the temperature was +30°C. The wind velocity did not exceed 2 m/s^{-1}, but from 11.00 a.m. to 1.00 p.m. the incerase of the wind velocity up to 5...7 m/s^{-1} was observed.

Thus, the essential influence of different atmospheric phenomena on the value and variation law of dispersion found is shown experimentally. The range of experimentally obtained $\Delta\varphi$ values was from -24° to $+64^{\circ}$.

3.FREQUENCY BAND CHARACTERISTICS OF COMMUNICATION LINES

In paper [10] it was shown that the envelope of rectangular radio pulse at the output of the dispersion radio channel can be calculated by the following relation

$$|Q(t,z)| = \frac{Q_0}{\sqrt{2}}\left\{\left[C(U)-C\left(U-\frac{\tau}{\tau_0}\right)\right]^2+\left[S(U)-S\left(U-\frac{\tau}{\tau_0}\right)\right]^2\right\}^{1/2}, \quad (2)$$

where $C(U)$ and $S(U)$ are Frenel integrals, $U=(t-zc_z^{-1})\,\tau_0^{-1}$ - is dimensionless parameter, c_z is group velocity, τ is duration of initial pulse, Q_0 is pulse amplitude at the channel output, τ_0 is signal detection time at the channel output.
In expression (2) the value τ_0 is determined as follows

$$\tau_0 = \left[2\pi z c^{-1}\left|\varkappa(\omega)\right|_{\omega=\omega_0}\right]^{1/2}, \quad (3)$$

where ω_0 is radio pulse carrier frequency.
In expression (3) $\varkappa(\omega)$ is a function characterising the law of dispersion variation in the vicinity of the point $\omega=\omega_0$ which has the following form

$$\varkappa(\omega) = \frac{1}{2}\frac{d^2}{d\omega^2}\left[\omega n(\omega)\right]_{\omega=\omega_0}. \quad (4)$$

It follows from relation (2) that the pulse envelope mode at the dispersion channel output in function of U parameter essentially depends on the relation τ/τ_0. The calculations showed that the relation $\tau/\tau_0 \simeq 1.6$ is the threshold one, but when $\tau/\tau_0 < 1.6$ the pulse mode at the channel output is distorted so much that its duration τ_{out} determined by the half value of its amplitude is more than τ. Therefore the limitation set on the duration decrease of the input radio pulse by the dispersing medium may be written in the following form

$$\tau_{min} \geqslant 1.6\,\tau_0 \qquad (5)$$

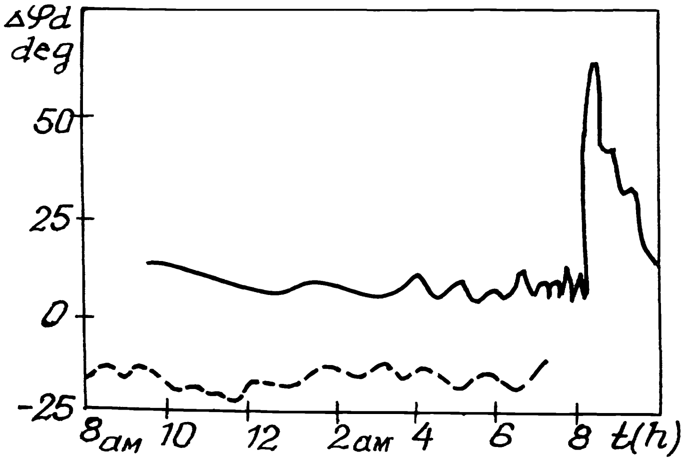

Fig.5.Results of observations of extremum values of phase invariant.

Let us express τ_0 by the $\Delta\varphi$ values. It is shown in paper [9] that the phase invariant of the modulated oscillation propagating in dispersing medium may be expressed by the dispersion parameter D determined in the vicinity of the point $\omega=\omega_0$

$$\Delta\varphi = z\,\Omega^2 D, \qquad (6)$$

where Ω is modulation frequency.

$$D = \frac{d^2k}{d\omega^2} = \frac{d^2}{d\omega^2}\Big[\omega n(\omega)\Big]_{\omega=\omega_0},$$ k -is wave number.

Comparing expressions for æ and D from relation (6) we may obtain

$$\text{æ}(\omega) = 0{,}5\,c\,\Delta\varphi\, z^{-1}\,\Omega^{-2}. \qquad (7)$$

Taking into account (7), the expression (3) may be written in the following form

$$\tau_0 = (\pi\,|\Delta\varphi|\,\Omega^{-2})^{1/2}. \qquad (8)$$

In this case condition (5) will have the form

$$\tau_{min} \geqslant 1{,}6\,(\pi\,|\Delta\varphi|\,\Omega^{-2})^{1/2}. \qquad (9)$$

We will treat the value $1/\tau_{min}$ as the maximum value of the radiowave propagation dispersion channel pass band Δf_{max}. Using condition (9) we may write

$$\Delta f_{max} = \Omega\,(2{,}56\,\pi\,|\Delta\varphi|)^{-1/2}. \qquad (10)$$

This expression allows to estimate communication lines band properties with the help of the $\Delta\varphi$ values measurements results. Applying measurements results presented in Figs.2...5 let us calculate variation of

Δf_{max} values of the experimental communication line. The largest values of Δf_{max} in communication line turned out to be observed in clear weather in spring and autumn. Under these conditions $\Delta f_{max} \geqslant 4.5$GHz. In clear weather in summer and winter Δf_{max} changed within 2.6... 4 GHz. After rain fall out in warm season (summer, beginnning of autumn) Δf_{max} decreased to 1.6...2 GHz. The motion of cold atmospheric fronts had the most important effect on the communication line band properties. Under these conditions the values of Δf_{max} decreased down to 1.05...1.5 GHz.

Thus systematic experimental investigations carried out by "phase invariant method" in the open near-surface communication line of millimeter range showed that in atmosphere "frequency windows" its surface layer manifests the properties of the medium with regular dispersion. The value and the law of the dispersion change have diurnal and season variation and are not connected to the dispersion in atmospheric gases and the presence of hydrometers in radiowaves propagation channel.

A technique is suggested for estimation of band properties of communication lines in which the necessary and sufficient calculation data are the phase invariant values. Estimates of the surface atmosphere layer conducted with application of this technique and the results of experimental investigations showed that surface communication lines of millimeter range possess the widest pass band in clear weather in spring and autumn. The most considerable decrease of the pass band takes place in the motion of cold atmospheric fronts.

The dispersion found in atmosphere "frequency windows" may by the most important factor limiting pass bands of surface communication lines of millimeter range compared with other known phenomena causing such limitations.

4.REFERENCES

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