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Influence of atmospheric wind on the propagation of radio waves

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Abstract – **Background.** It is necessary to study the influence of the physical characteristics of the atmosphere, in particular, wind on atmospheric turbulence and, consequently, on the characteristics of the radio signal it is shown. **Aim.** The dependence of the time-spectral function of the radio signal energy flux on the wind speed in the troposphere in the antenna plane is found. **Methods.** A method of transition from the Cartesian coordinate system in the antenna plane to the polar coordinate system of wave numbers has been developed. Based on this method the relationship between the Fourier spectral function of the correlation moment and the representation of the Bessel function is found. For the Fourier spectral function of the correlation moment, the previously obtained solution of the differential equation for the fluctuations of the eikonal amplitude of electromagnetic wave in a turbulent atmosphere at the front of the electromagnetic wave at the coordinate of the receiving antenna is used. Using the inverse Fourier transform the relationship between the time-spectral function of the radio signal energy flux and the time-correlation function of this flux is found. **Results.** Based on the study of the time-correlation function of the radio signal energy flow its relationship with the two-point correlation moment characterizing the fluctuations of the eikonal amplitude of the radio signal is found. To analyze the effect of wind, a turbulence model was used, reflecting the inertial turbulence interval, in which the energy flow from larger turbulent vortices to smaller vortices is determined by the viscous dissipation of the smallest vortices. **Conclusion.** Numerical calculations have shown that such a wind in the antenna plane blows away turbulent vortices in this plane, bettering the quality of the received radio signal.

Keywords – radio signal; atmospheric turbulence; atmospheric wind; time-correlation function; coordinate system of wave numbers; Fourier-spectral functions.

Introduction

The propagation of a radio signal from the transmitter to the receiving antenna depends on the physical characteristics of the atmosphere through which the radio signal travels. In particular, radio signal propagation in a turbulent atmosphere is affected by fluctuations in atmospheric pressure, temperature, humidity, time of day, etc.

The listed characteristics affect the refractive index of the medium. We confine ourselves to analyzing the propagation of radio waves in the troposphere, considering this medium as a non-electrically conductive gas mixture with a relative magnetic permeability equal to one, so that $n=\sqrt{\varepsilon}$, where ε is the relative permittivity of the medium. Let us pay special attention to the motion of the medium created by atmospheric wind, for which we consider two coordinates in the troposphere X_1 and X_2, Fig. 1. The figure also shows the direction of the radio signal along the X coordinate.

There are many empirical formulas describing the dependence of the refractive index on the characteristics of the atmosphere. For example, in [1] the formula is used for centimeter radio waves:

$$n = 1 + 10^{-6}\frac{79p}{T}\left(1+\frac{7800\vartheta}{T}\right), \tag{1}$$

where p is pressure in millibars; T is absolute temperature; ϑ is specific humidity (ratio of water vapor density to the density of moist air).

1. Time-correlation function of radio signal energy flux

The energy flux of the radio signal, Fig. 1, incident on the antenna, can be found by the formula [2]:

$$P(\mathbf{X},t)=\int_{\Sigma} I(\mathbf{X},t)\,dX = I(0)\int_{\Sigma} e^{2\chi'(\mathbf{X},t)}d\mathbf{X}, \tag{2}$$

where $I(\mathbf{X},t)$ is the radio signal intensity depending on the coordinate $\mathbf{X}$ and time t due to atmospheric turbulence, $I(\mathbf{X},t)=I(0)e^{2\chi'(\mathbf{X},t)}$, $I(0)$ is the constant component of radio signal intensity at the coordi-

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nate $\mathbf{X} = 0$, where turbulence is absent. The function $\chi'(\mathbf{X},t)$ characterizes the fluctuations of the radio signal eikonal amplitude [3] at coordinate $\mathbf{X}$ due to atmospheric turbulence. The coefficient 2 is used because the intensity of the radio signal (or the modulus of the Poynting vector) is proportional to the square of the electric and magnetic field strengths in the electromagnetic wave, and Σ is the area of the circular receiving antenna at the coordinate of $X = L$, Fig. 1.

We shall only consider small fluctuations, so that formula (2) is reduced to the following:

$$P(\mathbf{X},t) = I(0)\int_{\Sigma}\left(1+2\chi'(\mathbf{X},t)\right)d\mathbf{X} = \tag{3}$$
$$= P(\mathbf{X},0) + I(0)\int_{\Sigma} 2\chi'(\mathbf{X},t)\,d\mathbf{X}.$$

The time-correlation function of the energy flux of the radio signal at the coordinates $\mathbf{X}_1$ and $\mathbf{X}_2$ shall be written as:

$$R_{PP}(\tau) = \Big\langle \Big(P(\mathbf{X}_1,t) - \big\langle P(\mathbf{X}_1,0)\big\rangle\Big)\times \tag{4}$$
$$\times\Big(P(\mathbf{X}_2,t+\tau) - \big\langle P(\mathbf{X}_2,0)\big\rangle\Big)\Big\rangle / \langle P_0\rangle^2 =$$
$$= \left\langle \left(I(0)\int_{\Sigma} 2\chi'(\mathbf{X}_1,t)\,d\mathbf{X}_1 \right)\times\right.$$
$$\left.\times\left(I(0)\int_{\Sigma} 2\chi'(\mathbf{X}_2,t+\tau)\,d\mathbf{X}_2 \right)\right\rangle / I^2(0)\Sigma^2 =$$
$$= \frac{4}{\Sigma^2}\int_{\Sigma}\int_{\Sigma}\big\langle \chi'(\mathbf{X}_1,t)\chi'(\mathbf{X}_2,t+\tau)\big\rangle d\mathbf{X}_1 d\mathbf{X}_2 =$$
$$= \frac{4}{\Sigma^2}\int_{\Sigma}\int_{\Sigma} B_{\chi\chi}\,d\mathbf{X}_1 d\mathbf{X}_2,$$

where $P_0 = I(0)\Sigma$ is the radio signal energy flux (radio signal power) in the unperturbed atmosphere; τ is the time of propagation of radio signal pulsations due to turbulence (but not the radio signal itself) over the distance between the coordinates $\mathbf{X}_1$ and $\mathbf{X}_2$, equal to the time of propagation of turbulent pulsations.

We shall consider the spectral representation of the correlation moment $B_{\chi\chi}$ in the form of a Fourier integral:

$$B_{\chi\chi} = \big\langle \chi'(\mathbf{X}_1,t)\chi'(\mathbf{X}_2,t+\tau)\big\rangle = \tag{5}$$
$$= \int e^{-i\mathbf{k}'(\mathbf{X}_1-\mathbf{X}_2)} F_{\chi\chi}(\mathbf{k}',\tau)\,d\mathbf{k}',$$

where $\mathbf{k}'$ is the wave vector of electromagnetic fluctuations (wave vector characterizing fluctuations of radio signal eikonal amplitude due to turbulence), $F_{\chi\chi}(\mathbf{k}',\tau)$ the spectral function of correlation momentum $B_{\chi\chi}$.

Substituting (5) into (4), we find the Fourier integral of the time-correlation function of the radio energy flux:

$$R_{PP}(\tau) = \frac{4}{\Sigma^2}\int_{\Sigma}\int_{\Sigma}\int e^{-i\mathbf{k}'(\mathbf{X}_1-\mathbf{X}_2)}\times \tag{6}$$
$$\times F_{\chi\chi}(\mathbf{k}',\tau)\,d\mathbf{k}' d\mathbf{X}_1 d\mathbf{X}_2.$$

2. Transition from the Cartesian coordinate system in the antenna plane to the polar coordinate system of wave numbers

We shall consider the integral $\int_{\Sigma} e^{i\mathbf{kX}}d\mathbf{X}$ in the antenna plane. When finding this integral, to simplify the notation, we replace $\mathbf{k}'$ with $\mathbf{k}$:

$$\int_{\Sigma} e^{i\mathbf{kX}}d\mathbf{X} = \iint_{\Sigma} e^{i(k_2Y+k_3Z)}d\mathbf{X}. \tag{7}$$

The value of $\mathbf{kX}$ in the antenna plane can be represented as a scalar product of $\mathbf{kX} = k_2Y + k_3Z$.

To find the integral (7), two interrelated coordinate systems must be considered in the antenna plane at $X = L$: the Cartesian coordinate system $\mathbf{X}(X = L, Y, Z)$ and the coordinate system of the wave numbers $\mathbf{k}_0(k_1, k_2, k_3) = \mathbf{k}_0(k_1, k)$.

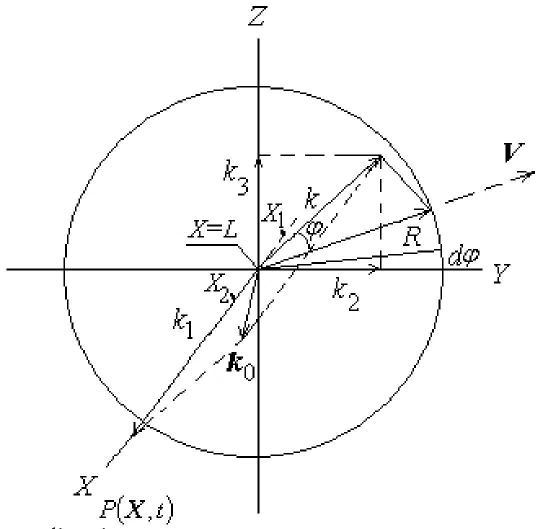
In (7) we shall transfer to the polar coordinates in the wave number coordinate system. Arc modulus in the plane of the antenna is as follows:

$$|d\mathbf{X}| = \sqrt{dY^2 + dZ^2} = \beta\sqrt{k_3^2 d\varphi^2 + k_2^2 d\varphi^2} = \beta k\,d\varphi, \tag{8}$$

where $k = \sqrt{k_3^2 + k_2^2}$ is the polar radius in the coordinate system of the wave numbers (the total sum vector $\mathbf{k}_0$ does not participate in this analysis); $d\varphi$ is the differential of the angular polar coordinate in this coordinate system; β is the dimensional coefficient of transition from Cartesian coordinates to the coordinate system of the wave numbers $[\beta] = \text{m}^2$. According to Fig. 1, the relation of differentials in the Cartesian coordinate system and the polar coordinate system of wave numbers has the form $dY = \beta k_3 d\varphi$ and $dZ = \beta k_2 d\varphi$.

The integral $\int_{\Sigma} e^{i\mathbf{kX}}d\mathbf{X}$ can be found as an integral along the contour of a circle of radius R in the polar coordinate system of wave numbers. At the same time $\Sigma = \pi R^2$.

Let us pass from the polar coordinate system of wave numbers to the antenna radius R in the Cartesian coordinate system. Taking into account the polar coordinates of $\beta k = R\cos\varphi$, in Fig. 1, in accord-



direction
of radio signal

Fig. 1. Relationship between the Cartesian coordinate system and the wave number coordinate system in the antenna plane
Рис. 1. Связь декартовой системы координат и системы координат волновых чисел в плоскости антенны

ance with (8) we have $\mathbf{k}d\mathbf{X} = kR\cos\varphi d\varphi$ and $\mathbf{kX} = kR\cos\varphi$.

Thus, we find:

$$\int_{\Sigma} e^{i\mathbf{kX}} d\mathbf{X} = \mathbf{n}\int_{0}^{2\pi} e^{ikR\cos\varphi} R\cos\varphi d\varphi = \tag{9}$$

$$= \mathbf{n}R\int_{0}^{2\pi} e^{ikR\cos\varphi}\cos\varphi d\varphi,$$

where $\mathbf{n}$ is a unit vector in the direction of the $\mathbf{X}$ coordinate. The limits of integration from Cartesian coordinates to the polar coordinate system of wave numbers have been replaced.

In formula (9) we use the known representation of the Bessel function [4]:

$$J_m(Z) = \frac{(-i)^m}{\pi}\int_{0}^{\pi} e^{iZ\cos t}\cos mt dt. \tag{10}$$

Therefore, for the integral (9) at $m = 1$, we find:

$$\int_{\Sigma} e^{i\mathbf{kX}} d\mathbf{X} = \mathbf{n}R\frac{2\pi}{-i}J_1(kR) = \tag{11}$$

$$= -\mathbf{n}\frac{2\pi R^2}{iR}J_1(kR) = -\mathbf{n}\frac{2\Sigma}{iR}J_1(kR).$$

Thus, the double integral is equal to:

$$\int_{\Sigma}\int_{\Sigma} e^{-i\mathbf{k}(\mathbf{X}_1-\mathbf{X}_2)} d\mathbf{X}_1 d\mathbf{X}_2 = \left(\frac{2}{R}J_1(kR)\right)^2\Sigma^2. \tag{12}$$

Applying the inverse Fourier transform in time τ to formula (6) and returning to the previous notation $\mathbf{k}'$, we find the time spectral function of the energy flux of the radio signal:

$$F_{PP}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{i\omega\tau}R_{PP}(\tau)d\tau = \tag{13}$$

$$= \frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{i\omega\tau}\frac{4}{\Sigma^2}\int\int_{\Sigma}\int_{\Sigma} e^{-i\mathbf{k}'(\mathbf{X}_1-\mathbf{X}_2)}\times$$

$$\times F_{\chi\chi}(\mathbf{k}',\tau)d\mathbf{k}'d\mathbf{X}_1 d\mathbf{X}_2 d\tau =$$

$$= \frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{i\omega\tau}\frac{4}{\Sigma^2}\int\left(\frac{2}{R}J_1(k'R)\right)^2\Sigma^2 F_{\chi\chi}(\mathbf{k}',\tau)d\mathbf{k}'d\tau =$$

$$= \frac{2}{\pi}\int\left(\frac{2}{R}J_1(k'R)\right)^2 d\mathbf{k}'\int_{-\infty}^{+\infty} e^{i\omega\tau}F_{\chi\chi}(\mathbf{k}',\tau)d\tau,$$

where ω is the frequency of turbulent pulsations, equal to the frequency of pulsations of the radio signal.

The function $F_{\chi\chi}(\mathbf{k}',\tau)$ can be obtained using the solution of the differential equation for fluctuations in the amplitude of the eikonal χ' of an electromagnetic wave in a turbulent atmosphere [3]:

$$F_{\chi\chi}(\mathbf{k}') = \mu\zeta^4\int_{0}^{L}\int_{0}^{L}\sin\frac{k'^2(L-\upsilon)}{2k}\times \tag{14}$$

$$\times\sin\frac{k'^2(L-\xi)}{2k}F_{nn}(\mathbf{k}',\upsilon,\xi)d\upsilon d\xi,$$

where ζ is the wave vector of turbulent pulsations; μ is a constant scale coefficient of proportionality between the correlation moment of the refractive index and the correlation moment of fluctuations in the amplitude of the eikonal radio signal $B_{nn} = \mu B_{\chi\chi}$ (where the two-point correlation functions $B_{nn} = \langle n_1(X_1)n_1(X_2)\rangle$ and $B_{\chi\chi} = \langle\chi'(X_1)\chi'(X_2)\rangle$), υ and ξ are the coordinates of the two-point source of turbulence on the electromagnetic wave; $F_{nn}(\mathbf{k}',\upsilon,\xi)$ is the spectral function of the pulsations of the refractive index; $\mathbf{k}$ is the wave vector electromagnetic wave, $\mathbf{k}'$ is the wave vector characterizing fluctuations in the amplitude of the radio signal eikonal.

Formula (14) is written at the front of the electromagnetic wave at $X = X_1 = X_2 = L$, i.e. at the coordinate of the receiving antenna. We also use a single coordinate of the source of the effect of turbulence on the electromagnetic wave $\upsilon = \xi$. In this case, formula (14) is simplified:

$$F_{\chi\chi}(\mathbf{k}') = \mu\zeta^2\int_{0}^{L}\sin^2\frac{k'^2(L-\xi)}{2k}F_{nn}(\mathbf{k}',\xi)d\xi, \tag{15}$$

where $F_{nn}(\mathbf{k}',\xi)$ is the three-dimensional spectral function of the field of fluctuations of the refractive index $n'(\mathbf{X})$.

3. Influence of atmospheric wind on pulsation correlation relations of atmospheric parameters

We shall introduce atmospheric wind into the analysis of the radio propagation process and investigate its influence on the tropospheric parameters that determine the effect on this propagation process.

Consider the correlation function of the refractive index pulsations in the presence of wind:

$$B_{nn}\left(\mathbf{X}_1-\mathbf{X}_2+\mathbf{V}\tau\right)=\left\langle n'\left(\mathbf{X}_1,t\right)n'\left(\mathbf{X}_2,t+\tau\right)\right\rangle = \tag{16}$$

$$=\left\langle n'\left(\mathbf{X}_1,t\right)n'\left(\left(\mathbf{X}_2-\mathbf{V}\tau\right),t\right)\right\rangle,$$

where $\mathbf{V}$ is the component of the wind velocity in the plane perpendicular to the coordinates of the vectors $\mathbf{X}_1$ and $\mathbf{X}_2$. For the sake of certainty of the analysis, we assume that the coordinate points X_1 and X_2 lie in the plane of the antenna, Fig. 1, so that $X = X_1 = X_2 = L$. Consequently, the velocity vector $\mathbf{V}$ also lies in the plane of the antenna, Fig. 1, i.e. the wind is directed perpendicular to the direction of propagation of the radio signal.

To enter the air velocity in the atmosphere into formula (15), it must be taken into account that the shift in the argument of the correlation function (16) by $\mathbf{V}\tau$ corresponds to the multiplication in the spectral function by $e^{-i\mathbf{k}'\mathbf{V}\tau}$.

Consequently, formula (15) takes the following form:

$$F_{\chi\chi}\left(\mathbf{k}',\tau\right)= \tag{17}$$

$$=\mu\zeta^2\int_0^L \sin^2\frac{k'^2\left(L-\xi\right)}{2k}F_{nn}\left(\mathbf{k}',\xi\right)e^{-i\mathbf{k}'\mathbf{V}\tau}d\xi.$$

Let us substitute formula (17) into (13):

$$F_{PP}\left(\omega\right)=\frac{2}{\pi}\int\left(\frac{2}{R}J_1\left(k'R\right)\right)^2 d\mathbf{k}'\times \tag{18}$$

$$\times\int_{-\infty}^{+\infty} e^{i\omega\tau}F_{\chi\chi}\left(\mathbf{k}',\tau\right)d\tau=$$

$$=\frac{8\mu\zeta^2}{\Sigma}\int\int_{-\infty}^{+\infty}\int_0^L\left(J_1\left(k'R\right)\sin\frac{k'^2\left(L-\xi\right)}{2k}\right)^2\times$$

$$\times F_{nn}\left(\mathbf{k}',\xi\right)e^{i\left(\omega-\mathbf{k}'\mathbf{V}\right)\tau}d\mathbf{k}'d\xi d\tau,$$

where ξ integration goes along the entire length of the turbulence effect on the radio signal from 0 to L.

In formula (18), we perform integration by τ, using representation formula δ of the Dirac function [5]:

$$\int_{-\infty}^{+\infty} e^{i\left(\omega-\mathbf{k}'\mathbf{V}\right)\tau}d\tau=2\pi\delta\left(\omega-\mathbf{k}'\mathbf{V}\right). \tag{19}$$

As a result, we have:

$$F_{PP}\left(\omega\right)=\frac{16\pi\mu\zeta^2}{\Sigma}\int\int_0^L\left(J_1\left(k'R\right)\sin\frac{k'^2\left(L-\xi\right)}{2k}\right)^2\times \tag{20}$$

$$\times F_{nn}\left(\mathbf{k}',\xi\right)\delta\left(\omega-\mathbf{k}'\mathbf{V}\right)d\mathbf{k}'d\xi.$$

Next, using the properties of the δ-function, we exclude it from equation (20).

We shall replace the differential $d\mathbf{k}'=\mathbf{n}dk'd\varphi$, where φ is the angle between the vectors $\mathbf{k}'$ and $\mathbf{V}$, Fig. 1, and $\mathbf{n}$ is in this case a single vector in the direction of the vector $\mathbf{k}'$. Therefore, formula (20) is transformed into the following:

$$F_{PP}\left(\omega\right)=\frac{16\pi\mu\zeta^2}{\Sigma}\int\int_0^L\left(J_1\left(k'R\right)\sin\frac{k'^2\left(L-\xi\right)}{2k}\right)^2\times \tag{21}$$

$$\times F_{nn}\left(\mathbf{k}',\xi\right)\mathbf{n}dk'd\xi\int_{-\pi}^{\pi}\delta\left(\omega-\mathbf{k}'\mathbf{V}\right)d\varphi.$$

Using the δ-function property

$$\int_a^b f\left(Z\right)\delta\left(Z\right)dZ=f\left(0\right)$$

with $a<0<b$ and integrating by angle φ, we find:

$$\int_{-\pi}^{\pi}\delta\left(\omega-\mathbf{k}'\mathbf{V}\right)d\varphi=\int_{-\pi}^{\pi}\delta\left(\omega-k'V\cos\varphi\right)d\varphi= \tag{22}$$

$$=\int_{-\pi}^{\pi}\delta\left(Z\right)\frac{dZ}{\sqrt{\left(k'V\right)^2-\left(\omega-Z\right)^2}}=\frac{1}{\sqrt{\left(k'V\right)^2-\omega^2}},$$

where $Z=\omega-k'V\cos\varphi$.

Consequently, formula (21) takes the following form:

$$F_{PP}\left(\omega\right)=\frac{16\pi\mu\zeta^2}{\Sigma}\times \tag{23}$$

$$\times\int\int_0^L\left(J_1\left(k'R\right)\sin\frac{k'^2\left(L-\xi\right)}{2k}\right)^2\frac{F_{nn}\left(\mathbf{k}',\xi\right)dk'd\xi}{\sqrt{\left(k'V\right)^2-\omega^2}}.$$

Since there are no vector multipliers in expression (23), we omit the unit vector $\mathbf{n}$.

4. Atmospheric turbulence model

Further transformations of (23) are related to the adoption of a particular turbulence model.

We assume that the ripples of the wavenumber of the radio signal are proportional to the turbulent ripples of $\boldsymbol{\zeta} \sim \mathbf{k}'$. For simplicity of calculations, we shall assume that $\boldsymbol{\zeta} = \mathbf{k}'$. In this case, the spectral function of the pulsations of the wavenumber of the electromagnetic wave $F_{nn}(\mathbf{k}', \xi) \sim F(\boldsymbol{\zeta})$. In addition, as in [2], we assume that $F(\zeta) \approx \beta\zeta^{1/3}$, where the constant value of β does not depend on the wave number of turbulence ζ. This law mainly reflects the turbulent inertial region [3]. Turbulence in this region is in statistical equilibrium: the energy flux from larger turbulent vortices to smaller ones is determined by viscous dissipation of the smallest vortices.

In this case formula (23) is transformed into the following:

$$F_{PP}(\omega) = \frac{16\pi\mu\beta\zeta^2}{\Sigma} \int_0^{\zeta} \left(J_1(\zeta R)\right)^2 \times \tag{24}$$

$$\times \frac{\zeta^{\frac{1}{3}}}{\sqrt{(\zeta V)^2 - \omega^2}} d\zeta \int_0^L \sin^2 \frac{\zeta^2 (L - \xi)}{2k} d\xi.$$

The last integral in (24) is easily calculated:

$$\int_0^L \sin^2 \frac{\zeta^2 (L - \xi)}{2k} d\xi = \tag{25}$$

$$= \frac{L}{2} - \frac{1}{2} \int_0^L \left(\cos \frac{\zeta^2 (L - \xi)}{k} \right) d\xi =$$

$$= \frac{k}{2\zeta^2} \left(\frac{\zeta^2 L}{k} - \left(\sin \frac{\zeta^2 L}{k} \right) \right) \approx$$

$$\approx \frac{k}{12\zeta^2} \left(\frac{\zeta^2 L}{k} \right)^3 = \frac{1}{12} \left(\frac{\zeta^2}{k} \right)^2 L^3.$$

When calculating the integral (25) we used the approximate formula

$$\sin Z \approx Z - \frac{Z^3}{6}$$

Thus, formula (24) takes the following form:

$$F_{PP}(\omega) = \frac{4\pi\mu\beta\zeta^2 L^3}{3\Sigma k^2} \int_0^{\zeta} \frac{\zeta^{\frac{13}{3}} \left(J_1(\zeta R)\right)^2}{\sqrt{(\zeta V)^2 - \omega^2}} d\zeta = \tag{26}$$

$$= \frac{4\pi\mu\beta\zeta^2 L^3}{3\Sigma k^2 V} \int_0^{\zeta} \frac{\zeta^{\frac{13}{3}} \left(J_1(\zeta R)\right)^2}{\sqrt{\zeta^2 - \left(\frac{\omega}{V}\right)^2}} d\zeta.$$

Similar to [2], where the relative flicker characteristic of the received radio signal was used, we introduce the relative spectral function of the radio signal energy flux:

$$U_{PP} = \frac{\omega F_{PP}(\omega)}{4\left\langle \chi'^2 \right\rangle} = \frac{\gamma\zeta^2\Omega}{\Sigma k^2} \int_0^{\zeta} \frac{\zeta^{\frac{13}{3}} \left(J_1(\zeta R)\right)^2}{\sqrt{\zeta^2 - \Omega^2}} d\zeta, \tag{27}$$

where $\Omega = \omega / V$, is indicated and γ is a constant value. $\left\langle \chi'^2 \right\rangle \sim L^3$ is also accepted [1].

As mentioned earlier, the $\omega = \zeta u' = \zeta\sqrt{\frac{2}{3}E}$ value is the frequency of turbulent pulsations, where u' is the velocity of turbulent pulsations, $E = \frac{3}{2}\left\langle u'^2 \right\rangle$ is the energy of turbulence per unit mass of the medium (atmosphere) [6]. All coordinate components of the pulsation velocity are assumed to be the same. Thus, the value is

$$\Omega = \frac{\omega}{V} = \zeta \frac{u'}{V} = \zeta \frac{\sqrt{\frac{2}{3}E}}{V} \approx C \frac{\zeta^{\frac{1}{6}}}{V},$$

where C is a constant value.

In order not to overcomplicate the formulas, Kolmogorov's law was used for the energy of isotropic turbulence $E(\zeta) \sim \zeta^{-5/3}$ [3]. Substituting the expression for Ω into formula (27), we find:

$$U_{PP} = \frac{C_1 \zeta^{\frac{13}{6}}}{\Sigma k^2 V} \int_0^{\zeta} \frac{\zeta^{\frac{13}{3}} \left(J_1(\zeta R)\right)^2}{\sqrt{\zeta^2 - \frac{C^2 \zeta^{\frac{1}{3}}}{V^2}}} d\zeta = \tag{28}$$

$$= \frac{C_1 \zeta^{\frac{13}{6}}}{\Sigma k^2} \int_0^{\zeta} \frac{\zeta^{\frac{25}{6}} \left(J_1(\zeta R)\right)^2}{\sqrt{V^2 \zeta^{\frac{5}{3}} - C^2}} d\zeta,$$

where C_1 is a constant value.

Consider a real situation that can occur in the troposphere and stratosphere for medium and short waves [2]. We shall assume that the length of the radio wave and the scale of the turbulent ripple are equal to each other $\lambda \approx 10$ m. Hence, the wave numbers of the radio signal and the turbulent pulsations of $k = \zeta = 0{,}628\ \text{m}^{-1}$. In this case:

$$U_{PP} = \frac{C_1 \zeta^{\frac{1}{6}}}{\pi R^2} \int_0^{\zeta} \frac{\zeta^{\frac{25}{6}} \left(J_1(\zeta R)\right)^2}{\sqrt{V^2 \zeta^{\frac{5}{3}} - C^2}} d\zeta. \tag{29}$$

Fig. 2 shows the dependence of the relative spectral function $U_{PP}(V)$. The following values of the constants $C = 0{,}01\ \text{m}^{1/6}/\text{s}$, $C_1 = 100$, antenna radius

$R = 1$ m were used for calculation. The dimension of C_1 is determined by the fact that the relative spectral function $U_{PP}(V)$ is a dimensionless quantity.

As can be seen from the graph, with increasing atmospheric wind velocity in the antenna plane, the value of the spectral function $U_{PP}(V)$, and, consequently, the influence of turbulence on the radio signal decreases. This is because the wind blows away the turbulent ripples in the antenna plane, reducing their effect on the received radio signal.

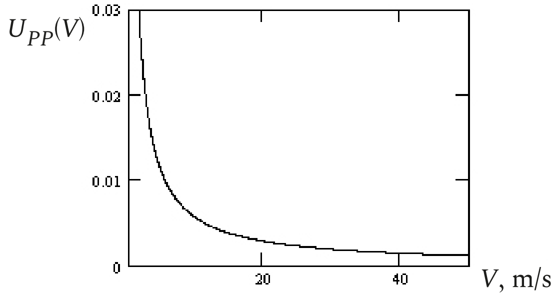


Fig. 2. Dependence of the relative correlation function of fluctuations in the radio signal energy flux on wind speed in the atmosphere

Рис. 2. Зависимость относительной корреляционной функции флуктуаций потока энергии радиосигнала от скорости ветра в атмосфере

Conclusion

The study of the time-correlation function $R_{PP}(\tau)$ of the radio signal energy flux at the coordinates X_1 and X_2, in Fig. 1 made it possible to establish its relationship with the two-point correlation moment characterizing fluctuations in the amplitude of the radio signal eikonal $B_{\chi\chi}$. Using the transition from the Cartesian coordinate system in the antenna plane to the polar coordinate system of the wave numbers, we found the relationship between the Fourier spectral function of the correlation moment $F_{\chi\chi}(\mathbf{k}',\tau)$ and the representation of the Bessel function. In this case, the previously obtained solution of the differential equation for the amplitude fluctuations of the amplitude of the eikonal χ' of an electromagnetic wave in a turbulent atmosphere at the front of the electromagnetic wave at the coordinate of the receiving antenna is used for the Fourier spectral function of the correlation moment.

Using the inverse Fourier transform, we found the relationship between the time-spectral function $F_{PP}(\omega)$ and the time-correlation function of the energy flux of the radio signal.

By studying the correlation function of the pulsations of refractive indices in the presence of wind B_{nn}, we found the dependence of the time-spectral function of the energy flux of the radio signal $F_{PP}(\omega)$ and the wind velocity in the troposphere in the antenna plane.

For the Fourier spectral function of the pulsations of the electromagnetic wave number (or the three-dimensional spectral function of the field of fluctuations of the refractive index) $F_{nn}(\mathbf{k}',\xi) \sim F(\boldsymbol{\zeta})$, we used a turbulence model, reflecting the inertial region of turbulence, in which the energy flux from larger turbulent vortices to smaller ones is determined by the viscous dissipation of the smallest vortices. This made it possible to find the dependence of the relative spectral function of the energy flux of the radio signal $U_{PP}(V)$ on the wind speed, which has a direction in the plane of the antenna, i.e. across the direction of the radio signal. The calculation shows that such a wind blows away turbulent vortices in the antenna plane, improving the quality of the received radio signal.

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Влияние атмосферного ветра на распространение радиоволн

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Аннотация – **Обоснование.** Показана необходимость исследования влияния физических характеристик атмосферы, в частности ветра, на атмосферную турбулентность и, следовательно, на характеристики радиосигнала. **Цель.** Найдена зависимость временной спектральной функции потока энергии радиосигнала от скорости ветра в тропосфере в плоскости антенны. **Методы.** Разработан метод перехода от декартовой системы координат в плоскости антенны к полярной системе координат волновых чисел. На основе этого метода прослежена связь между Фурье спектральной функцией корреляционного момента и представлением функции Бесселя. Для Фурье спектральной функции корреляционного момента использовано ранее полученное решение дифференциального уравнения для флуктуаций амплитуды эйконала электромагнитной волны в турбулентной атмосфере на фронте электромагнитной волны на координате приемной антенны. С помощью обратного преобразования Фурье найдена связь между временной спектральной функцией потока энергии радиосигнала и временной корреляционной функцией этого потока. **Результаты.** На основе исследования временной корреляционной функции потока энергии радиосигнала выявлена ее связь с двухточечным корреляционным моментом, характеризующим флуктуации амплитуды эйконала радиосигнала. Для анализа влияния ветра применена модель турбулентности, отражающая инерционную область турбулентности, в которой поток энергии от более крупных турбулентных вихрей к более мелким вихрям определяется вязкой диссипацией самых мелких вихрей. **Заключение.** Численный расчет показал, что ветер в плоскости антенны сдувает турбулентные вихри в этой плоскости, улучшая качество принимаемого радиосигнала.

Ключевые слова – радиосигнал; атмосферная турбулентность; атмосферный ветер; временная корреляционная функция; система координат волновых чисел; Фурье спектральные функции.

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