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Flickering of a radio-signal due to an atmospheric turbulence

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Abstract – **Background.** Turbulent fluctuations of the refractive index in the atmosphere lead to distortions during the passage of the radio signal. This can lead to distortion of the transmitted information due to the resulting fluctuations of the amplitude, phase and intensity of the electromagnetic wave that transmits the radio signal. Fluctuations in the intensity of the radio signal lead to flickering of the radio signal on the receiving antenna due to turbulent phenomena in the atmosphere, which are a complex multifunctional physical phenomenon. **Aim.** The problem of fluctuation of the intensity of the radio signal at the receiving antenna due to atmospheric turbulence is considered – the flicker of the radio signal. This problem is currently extremely actual, because there is a tendency of active, negative interference in the process of high-quality transmission of the radio signal on the background of naturally caused turbulent fluctuations. **Methods.** A theoretical analysis of the passage of a radio signal through a turbulent atmosphere is carried out. The spatial correlation function of fluctuations in the intensity of the received radio signal due to atmospheric turbulence is investigated. **Results.** The concept of the radio signal flicker characteristic is introduced as the average value of a random variable over the cross section of the receiving antenna – the dispersion of the logarithm of the radio signal power. A model of the occurrence of fluctuations in the case of two regions in the cross section of the receiving antenna with different levels of radio signal intensity is calculated. The correlation function for this model is found. **Conclusion.** Based on the Fourier-spectrum expansion of the two-point spatial correlation function of turbulent fluctuations of the refractive index, the dependence of the flicker characteristic of the radio signal on the wave number of turbulent fluctuations of the atmosphere is found. It is shown that the turbulence of the atmosphere has the greatest effect on the radio signal when the length of the electromagnetic wave is comparable to the scale of turbulent fluctuations.

Keywords – atmospheric turbulence; radio-signal; radio wave; fluctuations of intensity; two-point spatial turbulent correlations; Fourier spectrum.

Introduction

The main goal of communication network development in the Russian Federation is high-quality transmission of information using a radio signal [1]. However, in a turbulent atmosphere, fluctuations in the refractive index of air always affect various characteristics of the radio signal [2]. In addition, the radio signal characteristics are affected by solar activity [3], the atmospheric thermal conditions [4], air humidity [5], and environmental density.

Turbulent fluctuations in the atmosphere, being a stochastic wave process, interact with the deterministic electromagnetic wave process of the radio signal. These fluctuations, in particular, affect the amplitude and phase of the electromagnetic wave, affect the overall intensity of the signal received by the antenna, and scatter radio waves. Many of these effects are important for some practical problems related to the propagation of radio waves through the atmosphere. These effects can serve as sources of errors in communication systems, location, and radio navigation. The number of studies on the influence of turbulence is growing because of the expansion of the range of applied problems under consideration and because of studies aimed at clarifying the fundamental theoretical issues of the phenomenon [6–9].

1. Characteristics of radio signal flickering at the receiving antenna

Let us consider fluctuations in the energy flow or power of electromagnetic wave 1 due to atmospheric turbulence incident on receiving antenna 2 (Fig. 1) [10]. We call this process the flickering of the radio signal. Radio signal flickering creates interference and impairs the transmission of information over a radio channel. In Fig. 1, the origin of the coordinates is conventionally shifted down relative to the center of the receiving antenna 2. We will also conventionally assume that turbulence begins at position $X = 0$ and the receiving antenna is located on the X axis.

The total energy flux density or intensity of a plane electromagnetic wave is given by the following equation:

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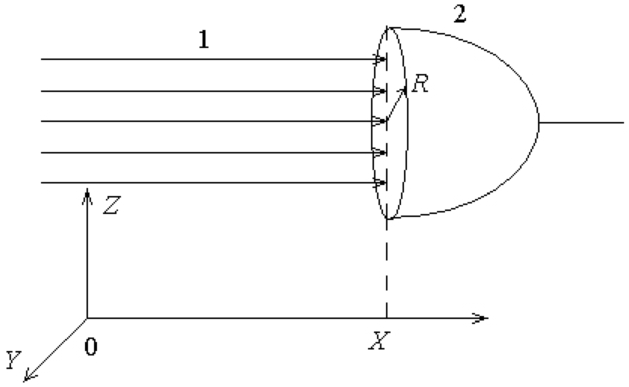

Fig. 1. Perception of a radio signal by a receiving antenna
Рис. 1. Восприятие радиосигнала приемной антенной

$$I(X)=I(0)\exp\left(2\chi'(X)\right), \tag{1}$$

where $\chi'(X)$ is the fluctuation of the radio signal eikon amplitude [11] on the X axis; and $I(0)$ is the constant component of the radio signal intensity at $X=0$, where there is no turbulence incident on the receiving antenna. Coefficient 2 was used because the radio signal intensity (or the magnitude of the Poynting vector) is proportional to the square of the electric and magnetic field strengths of the electromagnetic wave.

Fluctuations in the eikon amplitude and the amplitude of the electromagnetic wave are associated by the relation $\chi'=\ln(A/A_0)$ [11], where A is the total amplitude of the wave at position X, and A_0 is the constant component of the amplitude at $X=0$, where there is no turbulence.

Hence,

$$I(X)=I(0)\exp\left(2\ln\left(\frac{A}{A_0}\right)\right)= \tag{2}$$

$$=I(0)\exp\left(\ln\left(\frac{A}{A_0}\right)^2\right)=I(0)\left(\frac{A}{A_0}\right)^2=$$

$$=\frac{I(0)}{E_0^2}E^2=\frac{\varepsilon E_0^2 c}{E_0^2}E^2=\varepsilon E^2 c,$$

where $A=E$ is the electric field strength in the electromagnetic wave; ε is the relative dielectric permeability of the substance in which the radio signal propagates, and c is the speed of light in a vacuum. We consider the electric and magnetic components of the wave to have the same energy.

The radio signal energy flux incident on the antenna can be determined using the following equation:

$$P(X)=\int_\Sigma I(X)dX=I(0)\int_\Sigma e^{2\chi'(X)}dX. \tag{3}$$

where Σ is the area of the receiving antenna on the X axis.

It is more convenient to consider not the P value itself but its logarithm.

We consider the flickering characteristic of a radio signal to be the dispersion of a quantity $\ln P$, i.e., the quantity $\left\langle\left(\ln(P/P_0)\right)^2\right\rangle$, where the angle brackets indicate the spatial averaging of the amount; P_0 is the value of P at $X=0$ such that $\ln P_0=\langle\ln P\rangle$.

If we consider the distribution of turbulence over the antenna cross section at X to be isotropic, we obtain $P=I(0)\Sigma e^{2\chi'}$. In this case, the value is:

$$\left\langle\left(\ln\frac{P}{P_0}\right)^2\right\rangle=\left\langle\left(\ln\frac{I(0)\Sigma e^{2\chi'}}{P_0}\right)^2\right\rangle= \tag{4}$$

$$=\left\langle\left(\ln e^{2\chi'}\right)^2\right\rangle=4\left\langle\chi'^2\right\rangle,$$

where $P_0=I(0)\Sigma.$ is considered.

Let us introduce the dimensionless flickering characteristic of the received radio signal as follows:

$$G=\frac{1}{4\left\langle\chi'^2\right\rangle}\left\langle\left(\ln\frac{P}{P_0}\right)^2\right\rangle. \tag{5}$$

Let us transform the second factor in Eq. (5):

$$\left\langle\left(\ln\frac{P}{P_0}\right)^2\right\rangle=\left\langle\left(\ln P-\ln P_0\right)^2\right\rangle= \tag{6}$$

$$=\left\langle(\ln P)^2-2\ln P\ln P_0+(\ln P_0)^2\right\rangle=$$

$$=\left\langle(\ln P)^2\right\rangle-\left\langle 2\ln P\langle\ln P\rangle\right\rangle+\left\langle\left(\langle\ln P\rangle\right)^2\right\rangle=$$

$$=\left\langle(\ln P)^2\right\rangle-\langle\ln P\rangle^2=\ln\left(\left\langle P^2\right\rangle-\langle P\rangle^2\right)=\ln\frac{\left\langle P^2\right\rangle}{\langle P\rangle^2}.$$

When deriving Eq. (6), the relation $\ln P_0=\langle\ln P\rangle$ was used, and it was assumed that the value of P is logarithmically normal.

Thus, Eq. (5) is transformed as follows:

$$G=\frac{1}{4\left\langle\chi'^2\right\rangle}\ln\frac{\left\langle P^2\right\rangle}{\langle P\rangle^2}=\frac{1}{4\left\langle\chi'^2\right\rangle}\ln\frac{\left\langle P^2\right\rangle}{\langle I\rangle^2\Sigma^2}. \tag{7}$$

2. Correlation function of the radio signal intensity fluctuations

Let us consider the correlation function of fluctuations in the intensity of the received radio signal as follows:

$$B_{II}\left(\left|X_1-X_2\right|,\rho\right)=\left\langle I\left(X_1-\langle I\rangle\right)I\left(X_2-\langle I\rangle\right)\right\rangle. \quad (8)$$

where $\rho=\sqrt{Y^2+Z^2}$ is the radial coordinate that is not indicated in the arguments for intensities.

Considering that

$$\left\langle I\left(X_1-\langle I\rangle\right)I\left(X_2-\langle I\rangle\right)\right\rangle=$$

$$=\left\langle I\left(X_1\right)I\left(X_2\right)-\langle I\rangle^2\right\rangle=\left\langle I\left(X_1\right)I\left(X_2\right)\right\rangle-\langle I\rangle^2,$$

we determine that:

$$\left\langle P^2\right\rangle=\iint\limits_{\Sigma}\left\langle I\left(X_1\right)I\left(X_2\right)\right\rangle dX_1dX_2= \quad (9)$$

$$=\langle I\rangle^2\Sigma^2+\iint\limits_{\Sigma}B_{II}\left(\left|X_1-X_2\right|,\rho\right)dX_1dX_2\rho d\rho d\varphi,$$

where φ is the angular coordinate in the plane of the receiving antenna.

Let us consider the fluctuation in the received signal intensity in the cross section of the receiving antenna of radius R (Fig. 2).

Let us consider regions 3 and 4 in the radio signal cross section. These areas slightly differ in intensity, i.e., experience intensity fluctuation. We assume that both regions are circular with a radius of R. We assume that region 4 partially overlaps region 3 such that the circumference of region 4 passes through the center of region 3. Although the exact implementation of this model in practice is improbable, it enables the calculation of the radial correlation of radio signal intensities. In this model, the intensity correlation occurs over twice the area of the shaded segment (Fig. 2). The area of arbitrary segment 5 can be determined by subtracting the area of an equilateral triangle with a vertex angle 2φ from the area of the sector with the angle 2φ:

$$S_5=\varphi R^2-\frac{1}{2}\rho^2\sin 2\varphi= \quad (10)$$

$$=\varphi R^2-\rho^2\cos\varphi\sqrt{1-\cos^2\varphi}=$$

$$=R^2\left(\varphi-\frac{\rho^2}{R^2}\cos\varphi\sqrt{1-\cos^2\varphi}\right).$$

Therefore, for a double-shaded segment $\rho=R$, Eq. (10) can be presented as follows:

$$S_5=R^2\left(\varphi-\cos\varphi\sqrt{1-\cos^2\varphi}\right). \quad (11)$$

We denote $\cos\varphi=t$. Therefore, the double-shaded segment $2S_5$ can be presented as follows:

$$2S_5=2R^2\left(\arccos t-t\sqrt{1-t^2}\right). \quad (12)$$

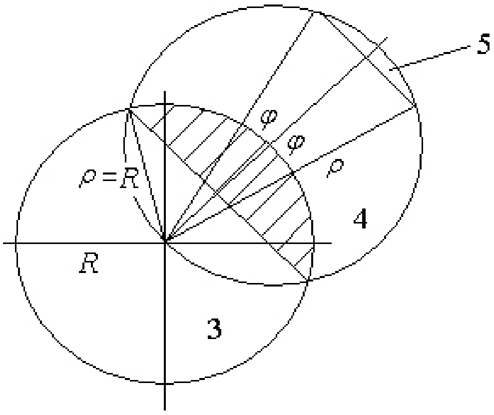

Fig. 2. To the calculation of the correlation of fluctuations in the intensity of the radio signal in the cross section of the antenna
Рис. 2. К расчету корреляции флуктуаций интенсивности радиосигнала в поперечном сечении антенны

In fact, using Eq. (12), we determined geometrically the integral in Eq. (9) with respect to the variable $\rho=2Rt$. Consequently,

$$\left\langle P^2\right\rangle=\iint\limits_{\Sigma}\left\langle I\left(X_1\right)I\left(X_2\right)\right\rangle dX_1dX_2= \quad (13)$$

$$=\langle I\rangle^2\Sigma^2+16\Sigma\iint\limits_{\Sigma}B_{II}\left(\left|X_1-X_2\right|,2Rt\right)S_5dX_1dX_2tdt.$$

Considering Eq. (12), Eq. (9) can be presented as:

$$\left\langle P^2\right\rangle=\langle I\rangle^2\Sigma^2+\frac{16}{\pi}\Sigma^2\iint\limits_{X_1,X_2}\int\limits_0^1 B_{II}\left(\left|X_1-X_2\right|,2Rt\right)\times \quad (14)$$

$$\times\left(\arccos t-t\sqrt{1-t^2}\right)tdtdX_1dX_2.$$

A similar equation, determined in a somewhat more formal way, was obtained in [8].

Substituting Eq. (14) into Eq. (7), we determine that:

$$G=\frac{1}{4\left\langle\chi'^2\right\rangle}\ln\left(1+\frac{16}{\pi}\iint\limits_{X_1,X_2}\int\limits_0^1\frac{B_{II}\left(\left|X_1-X_2\right|,2Rt\right)}{\langle I\rangle^2}\times\right. \quad (15)$$

$$\left.\times\left(\arccos t-t\sqrt{1-t^2}\right)tdtdX_1dX_2\right).$$

We notice that:

$$\frac{16}{\pi}\int\limits_0^1\left(\arccos t-t\sqrt{1-t^2}\right)tdt=1 \quad (16)$$

and substituting the value of Eq. (16) into Eq. (15) instead of unity, we transform Eq. (15) into the following form:

$$G=\frac{1}{4\left\langle\chi'^2\right\rangle}\ln\left(\frac{16}{\pi}\iint\limits_{X_1,X_2}\int\limits_0^1\left(1+\frac{B_{II}\left(\left|X_1-X_2\right|,2Rt\right)}{\langle I\rangle^2}\right)\times\right. \quad (17)$$

$$\times\left(\arccos t - t\sqrt{1-t^2}\right)tdtdX_1dX_2\Bigg).$$

Let us integrate the correlation function $B_{II}(|X_1 - X_2|,\ 2Rt)$ in the longitudinal direction. Considering that $I(X) = I(0)e^{2\chi'(X)}$, we transform the average value into the form of Eq. (9):

$$\langle I(X_1)I(X_2)\rangle = \langle I\rangle^2 + B_{II}(|X_1 - X_2|) = \quad (18)$$
$$= I^2(0)\langle \exp(2\chi'(X_1) + 2\chi'(X_2))\rangle =$$
$$= I^2(0)\exp\left\langle 2(\chi'(X_1) + \chi'(X_2))^2\right\rangle.$$

The last equality is valid for a normal two-dimensional joint distribution of random values $\chi'(X_1)$ and $\chi'(X_2)$. For a normally distributed random variable, the relation $\langle \exp(2\chi')\rangle = \exp 2\langle \chi'^2\rangle$ is valid.

We perform further transformations of Eq. (18):

$$\langle I\rangle^2 + B_{II}(|X_1 - X_2|) = \quad (19)$$
$$= I^2(0)\exp\left\langle 2(\chi'(X_1) + \chi'(X_2))^2\right\rangle =$$
$$= I^2(0)\exp\left\langle \left(2\chi'^2(X_1) + 2\chi'^2(X_2)\right)^2 + \right.$$
$$\left. + 4\chi'(X_1)\chi'(X_2)\right\rangle = I^2(0)\exp\left\langle 4\chi'^2 + 4B_{\chi\chi}\right\rangle,$$

where $B_{\chi\chi} = \langle \chi'(X_1)\chi'(X_2)\rangle$ are two-point correlation relations of the amplitude pulsations of an electromagnetic wave due to atmospheric turbulence [11]

Instead of the correlation function $B_{\chi\chi} = \langle \chi'(X_1)\chi'(X_2)\rangle$ we use the correlation function of fluctuations of the logarithm of the amplitude in the following form:

$$R_{\chi\chi}(|X_1 - X_2|) = \frac{B_{\chi\chi}(|X_1 - X_2|)}{\langle \chi'^2\rangle}. \quad (20)$$

Therefore, Eq. (19) can be presented as:

$$\langle I\rangle^2 + B_{II}(|X_1 - X_2|) = \quad (21)$$
$$= I^2(0)\exp\left\langle 4\chi'^2\left(1 + R_{\chi\chi}(|X_1 - X_2|)\right)\right\rangle.$$

Considering that $\langle I\rangle = I(0)\exp\left(2\langle \chi'\rangle^2\right)$, we obtain:

$$B_{II}(|X_1 - X_2|) = \frac{\langle I\rangle^2}{\exp\left(4\langle \chi'\rangle^2\right)}\times \quad (22)$$
$$\times\left(\exp\left\langle 4\chi'^2\left(1 + R_{\chi\chi}(|X_1 - X_2|)\right)\right\rangle\right) - \langle I\rangle^2 =$$
$$= \langle I\rangle^2\left(\exp\left\langle 4\chi'^2 R_{\chi\chi}(|X_1 - X_2|)\right\rangle - 1\right) =$$
$$= \langle I\rangle^2\left(\exp\left(\langle 4\chi'^2\rangle R_{\chi\chi}(|X_1 - X_2|)\right) - 1\right).$$

Substituting Eq. (22) into Eq. (17) and using $B_{II}(|X_1 - X_2|, 2Rt) = B_{II}(|X_1 - X_2|)B_{II}(2Rt)$, we determine the radial dependence of the function:

$$G(R) = \frac{1}{4\langle \chi'^2\rangle}\times \quad (23)$$
$$\times\ln\left(\frac{16}{\pi}\iint_{X_1,X_2}\int_0^1\left(\exp\left(\langle 4\chi'^2\rangle R_{\chi\chi}(|X_1 - X_2|, 2Rt)\right)\right)\times\right.$$
$$\left.\times\left(\arccos t - t\sqrt{1-t^2}\right)tdtdX_1dX_2\right) =$$
$$= \frac{1}{4\langle \chi'^2\rangle}\ln\left(\frac{16}{\pi}\int_0^1\exp\left(\langle 4\chi'^2\rangle R_{\chi\chi}(2Rt)\right)\times\right.$$
$$\left.\times\left(\arccos t - t\sqrt{1-t^2}\right)tdt\right).$$

In Eq. (23), integration over X_1 and X_2 is not performed.

Considering $B_{\chi\chi} = \langle \chi'^2\rangle R_{\chi\chi}$ and $B_{nn} = \mu B_{\chi\chi}$ [11], where B_{nn} is the two-point correlation of turbulent fluctuations of the refractive index, and μ is a constant scale proportionality factor, Eq. (23) can be presented as follows:

$$G(R) = \frac{1}{4\langle \chi'^2\rangle}\ln\left(\frac{16}{\pi}\int_0^1\exp\left(\frac{4}{\mu}B_{nn}(2Rt)\right)\times\right. \quad (24)$$
$$\left.\times\left(\arccos t - t\sqrt{1-t^2}\right)tdt\right).$$

For small values of t, the integrand in Eq. (24) is equal to $\exp\left(\frac{4}{\mu}B_{nn}(2Rt)\right)\frac{\pi}{2}t$; therefore, Eq. (24) can be presented as:

$$G(R) = \frac{1}{4\langle \chi'^2\rangle}\ln\left(8\int_0^1\exp\left(\frac{4}{\mu}B_{nn}(2Rt)\right)tdt\right). \quad (25)$$

3. Correlation function of the atmospheric turbulent fluctuations

The Fourier spectrum of the two-point correlation of turbulent fluctuations of the refractive index has the following form [11]:

$$B_{nn}\left(2Rt\right)=\int e^{-i\zeta\rho}F_{nn}\left(\zeta,\rho\right)d\zeta= \tag{26}$$

$$=\int_0^{\zeta} e^{-i\zeta 2Rt}F_{nn}\left(\zeta,2Rt\right)d\zeta,$$

where ζ is the wave vector of the turbulent pulsations.

Neglecting the dependence of the function F_{nn} on the radial coordinate $\rho=2Rt$, we accept $F_{nn}\left(\zeta\right)\approx\beta\zeta^{1/3}$, where β is a constant coefficient. This law mainly reflects the turbulent inertial region [11]. Turbulence in this region is in statistical equilibrium, and the energy flow from larger turbulent vortices to smaller ones is determined by the viscous dissipation of the smallest vortices.

Using the real part of the exponential in Eq. (26) as well, we obtain:

$$B_{nn}\left(2Rt\right)=\beta\int_0^{\zeta}\zeta^{\frac{1}{3}}\cos\left(2\zeta Rt\right)d\zeta, \tag{27}$$

The integral of Eq. (27) cannot be exactly determined in quadratures; therefore, we use the expansion $\cos\left(2\zeta Rt\right)=1-2\zeta^2R^2t^2$. In this case,

$$B_{nn}\left(2Rt\right)=\beta\int_0^{\zeta}\zeta^{\frac{1}{3}}\left(1-2\zeta^2R^2t^2\right)d\zeta= \tag{28}$$

$$=\beta\left(\frac{3}{4}\zeta^{\frac{4}{3}}-\frac{6}{10}\zeta^{\frac{10}{3}}R^2t^2\right).$$

Substituting Eq. (28) into Eq. (25), we obtain:

$$G\left(R\right)= \tag{29}$$

$$=\frac{1}{4\left\langle\chi'^2\right\rangle}\ln\left(8\int_0^1\exp\left(\frac{4}{\mu}\beta\left(\frac{3}{4}\zeta^{\frac{4}{3}}-\frac{6}{10}\zeta^{\frac{10}{3}}R^2t^2\right)\right)tdt\right)=$$

$$=\frac{1}{4\left\langle\chi'^2\right\rangle}\ln\left(\frac{5\mu}{\left(3\beta\zeta^{\frac{10}{3}}R^2\right)}\exp\left(\frac{3}{\mu}\beta\zeta^{\frac{4}{3}}\right)\times\right.$$

$$\left.\times\left(1-\exp\left(-\frac{12}{5\mu}\beta\zeta^{\frac{10}{3}}R^2\right)\right)\right).$$

The resulting equation is quite difficult to analyze. Let us simplify it by expanding the last exponent in the series $e^{\delta}=1+\delta$:

Thus, we obtain:

$$G\left(R\right)=\frac{1}{4\left\langle\chi'^2\right\rangle}\ln\left(4\exp\left(\frac{3}{\mu}\beta\zeta^{\frac{4}{3}}\right)\right)= \tag{30}$$

$$=\frac{1}{4\left\langle\chi'^2\right\rangle}\left(\ln 4+\frac{3\beta}{\mu}\zeta^{\frac{4}{3}}\right).$$

Considering Eq. (5), we reveal the dependence of the flickering characteristics of the radio signal on the wave number of turbulent pulsations:

$$\left\langle\left(\ln\frac{P}{P_0}\right)^2\right\rangle=4\left\langle\chi'^2\right\rangle G= \tag{31}$$

$$=\ln 4+\frac{3\beta}{\mu}\zeta^{\frac{4}{3}}=1{,}386+\frac{3\beta}{\mu}\zeta^{\frac{4}{3}}.$$

Figure 3 presents a graph of the dependence according to Eq. (31), constructed under the condition $\beta=\mu$. The dimension of the ratio is $\left[\beta/\mu\right]=\text{m}^{4/3}$. The deviation of the first term from zero is associated with the general approximation of the theoretical analysis. The condition must be met that at $\zeta=0$ (infinitely large turbulent pulsations), the flickering characteristic is

$$\left\langle\left(\ln\frac{P}{P_0}\right)^2\right\rangle=0$$

because $P=P_0$.

According to Fig. 3, the flickering of the radio signal perceived by the receiving antenna increases with the wave number of turbulent pulsations. In reality, the graph should start from point (0,0).

The turbulent pulsations have a maximum influence on a radio signal when the electromagnetic wavelength is near the scale of turbulent pulsations. Turbulent pulsations of various scales occur in the atmosphere. The table presents the approximate boundaries of the scale of turbulent pulsations in the troposphere, stratosphere, and ionosphere [6].

Turbulent pulsations of different scales do not exist separately. Turbulent pulsations on large scales include turbulent pulsations on smaller scales.

Thus, the scale of turbulent pulsations covers any range of radio wavelengths [12], particularly microwave radiation with a wavelength λ of 1–10 cm and very high-frequency radiation with $\lambda=10$ cm–10 m. Turbulence also affects long $(\lambda=10$–1 km), intermediate $(\lambda=1$ km–100 m), and short $(\lambda=100$ m–10 m) wavelength radiation.

Conclusion

Turbulent phenomena in the atmosphere associated with pulsations in the refractive index affect radio signal passage. They can distort transmitted

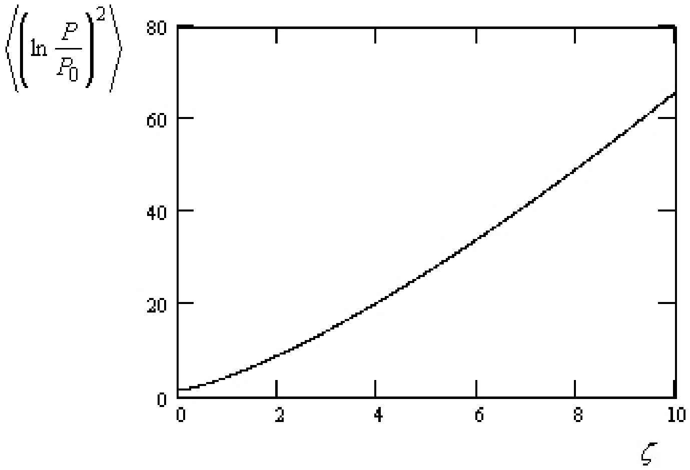

Fig. 3. Dependence of the characteristics of the scintillation of the radio signal at the receiving antenna on the wave number of turbulent atmospheric pulsations
Рис. 3. Зависимость характеристики мерцания радиосигнала на приемной антенне от волнового числа турбулентных пульсаций атмосферы

information because of fluctuations in the amplitude and phase of the electromagnetic wave that transmits the radio signal. Fluctuations in the intensity of the electromagnetic wave, leading to flickering of the radio signal at the receiving antenna, are of key importance. This study introduces the concept of radio signal flickering characteristics as the average value of a random variable over the cross section of the receiving antenna, i.e., the dispersion of the logarithm of the radio signal power.

Atmospheric turbulence is a complex physical phenomenon. The scale of turbulent pulsations varies greatly in magnitude from 0,5 cm to 20 km. In this case, turbulent pulsations of small scales are included as components in turbulent pulsations of large scales. Atmospheric turbulence has the greatest influence on radio signals when the length of the electromagnetic wave is comparable to the scale of turbulent pulsations.

In this study, we managed to calculate the situation when the size of the turbulent pulsation occupies a certain segment of the circular receiving antenna. In this case, rather simple relations are obtained for the correlation function of fluctuations in the received radio signal intensity. Using the Fourier spectrum of the two-point correlation of turbulent fluctuations of the refractive index in the so-called inertial region of turbulence, an association was determined between the characteristics of a radio signal flickering at the receiving antenna and the wave number of turbulent pulsations of the atmosphere. The flickering characteristic of the radio signal increases with the wave number of turbulent pulsations.

Table. Approximate boundaries of the scales of turbulent pulsations in the troposphere, stratosphere and ionosphere
Таблица. Примерные границы масштабов турбулентных пульсаций в тропосфере, стратосфере и ионосфере

Environment	λ_m	λ_0
Troposphere	1,4 km	1 km
Stratosphere	3 km	0,5 km
Ionosphere	20 km	10 m

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Мерцание радиосигнала за счет турбулентности атмосферы

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Аннотация – **Обоснование.** Турбулентные пульсации показателя преломления в атмосфере приводят к искажениям при прохождении радиосигнала. Это может создать искажение передаваемой информации за счет возникающих пульсаций амплитуды, фазы и интенсивности электромагнитной волны, которая передает радиосигнал. Флуктуации интенсивности радиосигнала приводят к мерцанию радиосигнала на приемной антенне за счет турбулентных явлений в атмосфере, которые представляют собой сложное многофункциональное физическое явление. **Цель.** Рассмотрена проблема флуктуации интенсивности радиосигнала на приемной антенне за счет турбулентности атмосферы – мерцание радиосигнала. Эта проблема в настоящее время является исключительно актуальной, т. к. существует тенденция активного, негативного вмешательства в процесс качественного прохождения радиосигнала на фоне природно обусловленных турбулентных пульсаций. **Методы.** Проведен теоретический анализ прохождения радиосигнала через турбулентную атмосферу. Исследована пространственная корреляционная функция флуктуаций интенсивности принимаемого радиосигнала за счет турбулентности атмосферы. **Результаты.** Введено понятии характеристики мерцания радиосигнала как среднего по сечению приемной антенны значения случайной величины – дисперсии логарифма мощности радиосигнала. Рассчитана модель возникновения флуктуации в случае двух областей в сечении приемной антенны с различными уровнями интенсивности радиосигнала. Найдена корреляционная функция для этой модели. **Заключение.** На основе разложения в Фурье-спектр двухточечной пространственной корреляционной функции турбулентных пульсаций показателя преломления найдена зависимость характеристики мерцания радиосигнала от волнового числа турбулентных пульсаций атмосферы. Показано, что наибольшее влияние на радиосигнал турбулентность атмосферы оказывает, когда длина электромагнитной волны сравнима с масштабом турбулентных пульсаций.

Ключевые слова – атмосферная турбулентность; радиосигнал; радиоволны; флуктуации интенсивности; двухточечные турбулентные корреляции; Фурье-спектр.

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