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Some features of a radio signal interaction with a turbulent atmosphere

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Abstract – On the basis of the solution of Maxwell's equations system for electromagnetic radiation in a turbulent atmosphere the differential effective section of scattering of this radiation on turbulence is found. Dependence of scattering section on wave length and an angle of scattering is investigated. It is shown that interaction of electromagnetic radiation and turbulence of an atmosphere is interaction of the determined electromagnetic wave process with stochastic turbulent wave process. It is marked, that the wave vector of scattering electromagnetic radiation is proportional to a wave vector of turbulence.
Keywords – turbulence of an atmosphere; scattering of electromagnetic waves; section of scattering; scale of turbulence; Fourier-spectrum of turbulence.

Introduction

Super-high-frequency (SHF) electromagnetic radiation with a wavelength λ = 1–10 cm and ultra-high-frequency (UHF) electromagnetic radiation with λ = = 10–100 cm are widely used in television and radio detection and ranging.

These types of electromagnetic radiation, in the absence of an atmosphere in the region of a planet's gravitational field, propagate rectilinearly, which limits radio communication on these waves to a distance of 40–50 km. Longer waves diffract on the spherical surface of the Earth, which is a reason for the reception of radio signals beyond the line of sight. However, the presence of an atmosphere also raises the possibility of perceiving SHF and UHF radiation beyond the planetary horizon. This possibility, in particular, is due to the reflection of radiation from the ionized layer in the atmosphere's upper layers, in the troposphere at an altitude of 10–12 km in temperate latitudes. In addition, the effect of perceiving SHF and UHF radiation beyond the horizon is also associated with turbulence in the atmosphere, particularly the stratosphere at an altitude of 12–50 km with a relative dielectric permeability of $\varepsilon \approx 1$.

The process of electromagnetic wave propagation in the atmosphere was previously studied by many scientists, in particular [1–5].

Physically, the interaction of electromagnetic radiation and atmospheric turbulence is one of a deterministic electromagnetic wave process with a stochastic turbulent wave process.

This article aimed to analyze the influence of turbulent pulsations in the atmosphere on electromagnetic radiation.

1. Differential effective scattering cross section of ultrashort-wave electromagnetic radiation in a turbulent atmosphere

To analyze the propagation of ultrashort-wave electromagnetic radiation in the atmosphere in the range of λ = 10–100 cm, it will be considered an approximate nonconducting medium with dielectric permeability $\varepsilon = n^2$ and magnetic permeability $\mu = 1$, where n is the refractive index of atmospheric matter.

Maxwell's system of equations for electromagnetic waves propagating in the atmosphere has the following form:

$$\operatorname{curl}\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t}, \tag{1}$$

$$\operatorname{curl}\mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t}, \tag{2}$$

$$\operatorname{div}\mathbf{D} = 0, \tag{3}$$

$$\operatorname{div}\mathbf{H} = 0. \tag{4}$$

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In Eqs. (1)–(4), **E**, **H**, and **D** are the electric and magnetic field strengths and the electrical induction of an electromagnetic wave, respectively, t is time, and c is the speed of light in a vacuum, approximately equal to the speed of light in the atmosphere.

We present the material equation in the following form:

$$\mathbf{D} = \varepsilon\mathbf{E}. \tag{5}$$

We assume that the refractive index of the atmosphere differs slightly from unity because of fluctuations in its parameters, such as pressure, temperature, and humidity. Therefore, we assume:

$$n = 1 + n^{/}, \tag{6}$$

where $n^{/}$ are random pulsations of the refractive index. The value of $n^{/}$ is on the order of 10^{-8}–10^{-6} [6].

Considering that $\varepsilon = n^2$, and $n^{/} \ll 1$, we also reveal the following relation:

$$\varepsilon = 1 + 2n^{/} + n^{/2} \approx 1 + 2n^{/} = 1 + \varepsilon^{/}. \tag{7}$$

Dielectric permeability pulsations $\varepsilon^{/} = 2n^{/}$, despite their small magnitude, scatter electromagnetic waves in the atmosphere.

Considering the sinusoidal–oscillatory nature of electromagnetic waves, Eqs. (1) and (2) can be presented in a form that excludes the time derivatives of the field strengths in the wave:

$$\operatorname{curl}\mathbf{E} = ik\mathbf{H}, \tag{8}$$

$$\operatorname{curl}\mathbf{H} = -ik\mathbf{D}. \tag{9}$$

The energy flux density of electromagnetic oscillations, the Poynting vector [7], has the form:

$$\mathbf{S} = \frac{c}{4\pi}\left(\mathbf{E}\times\mathbf{H}\right). \tag{10}$$

From Eq. (8), we determine the magnetic field strength:

$$\mathbf{H} = -\frac{i}{k}\operatorname{curl}\mathbf{E}. \tag{11}$$

Substituting Eq. (11) into Eq. (12), we determine the dependence of the Poynting vector on only the electric field strength of the wave:

$$\mathbf{S} = \frac{c}{4\pi}\left(\mathbf{E}\times\mathbf{H}\right) = -\frac{ci}{4\pi k}\left(\mathbf{E}\times\operatorname{curl}\mathbf{E}\right). \tag{12}$$

Let a plane electromagnetic wave with electric field strength $\mathbf{E}_0$ impinge on a conditionally allocated volume V (Fig. 1) containing turbulent atmospheric pulsations:

$$\mathbf{E}_0 = \mathbf{p}A_0 e^{i\mathbf{kX}}, \tag{13}$$

where **X** is the coordinate of the incident wave propagation; **p** is the unit vector in the plane of oscillation of the vector $\mathbf{E}_0$ perpendicular to the direction

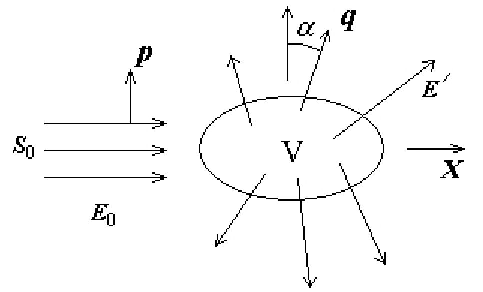

Fig. 1. Scattering of a plane electromagnetic wave (Poynting vector) by volume V with turbulent pulsations
Рис. 1. Рассеяние плоской электромагнитной волны (вектора Пойнтинга) объемом V с турбулентными пульсациями

of propagation of the wave, i.e., wave vector **k**; A_0 is the wave amplitude; and **kX** is the phase of the wave. We neglect the time component of the phase because Maxwell's equations in the form of Eqs. (8) and (9) are used.

According to Eq. (12), this wave has an energy flux density equal to

$$\mathbf{S}_0\left(\mathbf{X}\right) = -\frac{ci}{4\pi k}\left(\mathbf{E}_0 \times \left(\frac{\partial \mathbf{E}_0}{\partial X}\right)\right) = \tag{14}$$

$$= -\frac{ci}{4\pi k}\left(\mathbf{p}A_0 e^{i\mathbf{kX}} \times \mathbf{p}A_0 e^{i\mathbf{kX}} i\mathbf{k}\right) = \frac{cA_0^2}{4\pi}\frac{\mathbf{k}}{k}e^{i2\mathbf{kX}},$$

which considers that $\mathbf{p}^2 = 1$.

Because vector $\boldsymbol{k}$ is directed along the $\boldsymbol{X}$ coordinate, we determine the average value of the Poynting vector $(\lambda = 2\pi/k)$ over the wavelength:

$$\mathbf{S}_0 = \frac{cA_0^2}{4\pi}\frac{\mathbf{k}}{k}\frac{k}{2\pi}\int_0^{\frac{2\pi}{k}}\left(\operatorname{Re}\left(e^{i2kX}\right)\right)dX = \tag{15}$$

$$= \frac{cA_0^2}{4\pi}\frac{\mathbf{k}}{k}\frac{k}{2\pi}\left(\int_0^{\frac{2\pi}{k}}\cos^2\left(kX\right)dX\right) = \frac{cA_0^2}{8\pi}\frac{\mathbf{k}}{k}.$$

The electric field strength in volume V can be represented as

$$\mathbf{E} = \mathbf{E}_0 + \mathbf{E}^{/}, \tag{16}$$

where $\mathbf{E}^{/}$ corresponds to scattered electromagnetic waves.

Let us exclude the magnetic field strength from the system of Eqs. (8) and (9), finding the curl of Eq. (8):

$$\operatorname{curl}\operatorname{curl}\mathbf{E} = ik\operatorname{curl}\mathbf{H} = k^2\mathbf{D}. \tag{17}$$

Therefore, $k^2(\mathbf{D}_0 + \mathbf{D}^{/}) = \operatorname{curl}\operatorname{curl}(\mathbf{E}_0 + \mathbf{E}^{/})$, where $\mathbf{D}_0 = \varepsilon_0\mathbf{E}_0 = \mathbf{E}_0$, such that $\varepsilon_0 = 1$ is the dielectric permeability of the undisturbed atmosphere, and $\mathbf{D}^{/}$ is the turbulent pulsations of electrical induction. According to the Eq. (17), $k^2\mathbf{D}_0 = \operatorname{curl}\operatorname{curl}\mathbf{E}_0$, so we obtain the following equation for pulsating electrical characteristics:

$$k^2\mathbf{D}^{/} = \operatorname{curl}\operatorname{curl}\mathbf{E}^{/}, \tag{18}$$

In accordance with Eqs. (5) and (7), we obtain $\mathbf{D} = (1+2n^{/})\mathbf{E}$ or $\mathbf{D}_0 + \mathbf{D}^{/} = (1+2n^{/})(\mathbf{E}_0 + \mathbf{E}^{/})$. Therefore, $\mathbf{D}_0 + \mathbf{D}^{/} = (\mathbf{E}_0 + 2n^{/}\mathbf{E}_0 + \mathbf{E}^{/} + 2n^{/}\mathbf{E}^{/})$. Considering $\mathbf{D}_0 = \mathbf{E}_0$ and assuming $2n^{/}\mathbf{E}_0 + \mathbf{E}^{/} \gg 2n^{/}\mathbf{E}^{/}$, we obtain the following expression:

$$\mathbf{D}^{/} = \mathbf{E}^{/} + 2n^{/}\mathbf{E}_0. \tag{19}$$

Excluding the value $\mathbf{E}^{/}$ from the system of equations (18) and (19), we reveal that $k^2\mathbf{D}^{/} = \operatorname{curl}\operatorname{curl}(\mathbf{D}^{/} - 2n^{/}\mathbf{E}_0)$. Considering the formula of vector analysis $\operatorname{curl}\operatorname{curl}\mathbf{D}^{/} = \operatorname{grad}(\operatorname{div}\mathbf{D}^{/}) - \Delta\mathbf{D}^{/}$ and Eq. (3) in the form $\operatorname{div}\mathbf{D}^{/} = 0$, we obtain:

$$(\Delta + k^2)\mathbf{D}^{/} = -\operatorname{curl}\operatorname{curl}(2n^{/}\mathbf{E}_0). \tag{20}$$

The solution to wave equation (20) with a random right-hand side using Eq. (13) has the form:

$$\mathbf{D}^{/}(\mathbf{X}) = \tag{21}$$
$$= \frac{1}{4\pi}\operatorname{curl}\left(\operatorname{curl}\int\limits_{V} 2n^{/}(\mathbf{X}_1)\mathbf{E}_0(\mathbf{X}_1)\frac{e^{ik|\mathbf{X}-\mathbf{X}_1|}}{|\mathbf{X}-\mathbf{X}_1|}d\mathbf{X}_1\right) =$$
$$= \frac{A_0}{2\pi}\operatorname{curl}\left(\operatorname{curl}\mathbf{p}\int\limits_{V} n^{/}(\mathbf{X}_1)\frac{e^{i\mathbf{k}\mathbf{X}_1 + ik|\mathbf{X}-\mathbf{X}_1|}}{|\mathbf{X}-\mathbf{X}_1|}d\mathbf{X}_1\right).$$

Let $\mathbf{q} = \mathbf{X}/|\mathbf{X}|$ be the unit vector of the research direction (Fig. 1). We assume that no pulsations exist outside volume V; therefore $n^{/} = 0$, $\varepsilon = 1$, and $\mathbf{D} = \mathbf{E}$, along with Eqs. (5) and (6). The quantity $\mathbf{X}_1$ is inside volume V, and X is far enough from this volume, so in the denominator of the Eq. (21), the quantity $|\mathbf{X}-\mathbf{X}_1|$ can be replaced by $|\mathbf{X}-\mathbf{X}_1| \approx |\mathbf{X}|$ as the distance to the observation point. In addition, we assume $|\mathbf{X}-\mathbf{X}_1| = |\mathbf{X}-\mathbf{q}X_1| = |\mathbf{X}| - \mathbf{q}\mathbf{X}_1$, and

$$e^{i\mathbf{k}\mathbf{X}_1 + ik|\mathbf{X}-\mathbf{X}_1|} = e^{i\mathbf{k}\mathbf{X}_1 + ik(|\mathbf{X}| - \mathbf{q}\mathbf{X}_1)} = e^{ik|\mathbf{X}|}e^{i(\mathbf{k}-k\mathbf{q})\mathbf{X}_1},$$

and we present Eq. (21) in the following form:

$$\mathbf{E}^{/}(\mathbf{X}) = \tag{22}$$
$$= \frac{A_0}{2\pi}\operatorname{curl}\left(\operatorname{curl}\frac{\mathbf{p}e^{i\mathbf{k}|\mathbf{X}|}}{|\mathbf{X}|}\int\limits_{V} n^{/}(\mathbf{X}_1)e^{i(\mathbf{k}-k\mathbf{q})\mathbf{X}_1}d\mathbf{X}_1\right).$$

We consider that

$$\operatorname{curl}(\operatorname{curl}) = \nabla\times(\nabla\times) = \mathbf{q}\times(\mathbf{q}\times)\frac{\partial^2}{\partial|\mathbf{X}|^2},$$

and

$$\operatorname{curl}\left(\operatorname{curl}\frac{\mathbf{p}e^{ik|\mathbf{X}|}}{|\mathbf{X}|}\right) = \left(\mathbf{q}\times(\mathbf{q}\times\mathbf{p})\right)\frac{\partial^2}{\partial|\mathbf{X}|^2}\frac{e^{ik|\mathbf{X}|}}{|\mathbf{X}|} \approx$$
$$\approx \frac{k^2 e^{ik|\mathbf{X}|}}{|\mathbf{X}|}\left((\mathbf{q}\times\mathbf{p})\times\mathbf{q}\right).$$

Because the electromagnetic wavelength is small compared to the distance to the observation point $|\mathbf{X}| \gg \lambda$, when differentiating, we consider the denominator to be approximately constant, i.e., we actually use a flat geometry. Thus, we obtain:

$$\mathbf{E}^{/}(\mathbf{X}) = \frac{k^2 A_0 e^{ik|\mathbf{X}|}}{2\pi|\mathbf{X}|}G\left((\mathbf{q}\times\mathbf{p})\times\mathbf{q}\right), \tag{23}$$

where

$$G = \int\limits_{V} n^{/}(\mathbf{X}_1)e^{i(\mathbf{k}-k\mathbf{q})\mathbf{X}_1}d\mathbf{X}_1$$

is a parameter characterizing turbulent atmospheric pulsations.

Vector $(\mathbf{q}\times\mathbf{p})\times\mathbf{q} = |\sin\alpha|$, where α is the angle between vectors $\mathbf{p}$ and $\mathbf{q}$ (Fig. 1). The vector $(\mathbf{q}\times\mathbf{p})\times\mathbf{q}$ is perpendicular to vector $\mathbf{q}$.

Let us determine the flux density of scattered electromagnetic energy using Eq. (12):

$$\mathbf{S}^{/} = -\frac{ci}{4\pi k}\left(\mathbf{E}^{/}\times\operatorname{curl}\mathbf{E}^{/}\right) = \tag{24}$$
$$= -\frac{ci}{4\pi k}\left(\mathbf{E}^{/}\times\mathbf{q}\frac{\partial}{\partial|\mathbf{X}|}\mathbf{E}^{/}\right) = -\frac{ci}{8\pi k}\left(\mathbf{q}\frac{\partial}{\partial|\mathbf{X}|}\mathbf{E}^{/2}\right) =$$
$$= -\frac{ci}{8\pi k}\left(\mathbf{q}\frac{k^4 A_0^2}{4\pi^2}G^2|\sin\alpha|^2\frac{\partial}{\partial|\mathbf{X}|}\frac{e^{2ik|\mathbf{X}|}}{|\mathbf{X}|^2}\right) \approx$$
$$\approx -\frac{ci}{8\pi k}\left(\mathbf{q}\frac{k^4 A_0^2}{4\pi^2|\mathbf{X}|^2}G^2|\sin\alpha|^2 2ike^{2ik|\mathbf{X}|}\right) =$$
$$= \frac{c}{8\pi}\left(\mathbf{q}\frac{k^4 A_0^2}{4\pi^2|\mathbf{X}|^2}G^2|\sin\alpha|^2 2e^{2ik|\mathbf{X}|}\right) =$$
$$= \frac{ck^4 A_0^2|\sin\alpha|^2}{32\pi^3|\mathbf{X}|^2}G^2\mathbf{q}.$$

The derivation considers the average value $\operatorname{Re}(e^{2ik|\mathbf{X}|}) = 1/2$ over the wavelength.

The differential effective cross section for the process of scattering electromagnetic waves in volume V is equal to

$$d\sigma = \frac{dP}{|\mathbf{S}_0|}. \tag{25}$$

The energy flow (power) dP of electromagnetic waves scattered into a solid angle $d\Omega$ in the direction $\mathbf{q}$, considering Eq. (24), is equal to

$$dP = \left|\mathbf{S}^{/}\right|\left|\mathbf{X}\right|^2 d\Omega = \frac{ck^4 A_0^2 \left|\sin\alpha\right|^2}{32\pi^3} G^2 d\Omega. \qquad (26)$$

By substituting Eq. (15) into Eq. (26), we derive the following equation:

$$d\sigma = \frac{k^4 \left|\sin\alpha\right|^2}{4\pi^2} G^2 d\Omega = \frac{k^4 \sin^2\alpha}{4\pi^2} G^2 d\Omega. \qquad (27)$$

Thus, the differential effective cross section for the process of scattering electromagnetic waves by turbulent atmospheric pulsations obeys Rayleigh's fourth power law:

$$d\sigma \sim k^4 = \frac{16\pi^4}{\lambda^4}, \qquad (28)$$

Figure 2 presents the distribution of the differential effective cross section depending on angle α.

2. Influence of turbulent atmospheric characteristics on scattering of electromagnetic radiation

Let us explore in more detail the parameter

$$G = \int_V n^{/}\left(\mathbf{X}_1\right) e^{i(\mathbf{k}-k\mathbf{q})\mathbf{X}_1} d\mathbf{X}_1,$$

characterizing the atmospheric turbulization. The wave vector $\mathbf{k}-k\mathbf{q}$ is the difference between the wave vectors of the incident and scattered waves (Fig. 2).

To simplify the analysis, we will consider turbulence to be homogeneous and isotropic, i.e., it has quantitatively the same structure everywhere, and its statistical characteristics are independent of the direction.

Using the Fourier transform, we present the two-point correlation function $B_{nn}\left(\mathbf{X}_1 - \mathbf{X}_2\right) = \left\langle n^{/}\left(\mathbf{X}_1\right) n^{/}\left(\mathbf{X}_2\right)\right\rangle$ (angle brackets, as usual, mean spatial averaging) through the Fourier spectrum of turbulence $F_{nn}(\zeta)$:

$$B_{nn}\left(\mathbf{X}_1 - \mathbf{X}_2\right) = \int \exp\left(-i\zeta\left(\mathbf{X}_1 - \mathbf{X}_2\right)\right) F_{nn}(\zeta) d\zeta. \qquad (29)$$

In this case, $\boldsymbol{\zeta}$ is the wave vector of the turbulent spectrum. When an electromagnetic wave and turbulence interact, two wave processes interact, a deterministic electromagnetic wave process and a stochastic turbulent wave process. $\mathbf{k}-k\mathbf{q}$ is assumed to be proportional to the wave vector of the turbulent spectrum $\boldsymbol{\zeta}$ (Fig. 2). This assumption will be justified hereafter.

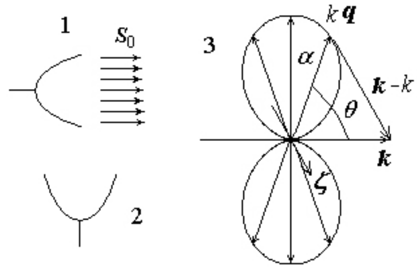

Fig. 2. Scheme for receiving electromagnetic waves scattered by turbulent pulsations of the atmosphere, 1 – emitting antenna, 2 – receiving antenna, 3 – angular wave scattering
Рис. 2. Схема приема электромагнитных волн, рассеянных на турбулентных пульсациях атмосферы, 1 – излучающая антенна, 2 – приемная антенна, 3 – угловое рассеяние волн

Thus, the mean square of the turbulence parameter G is equal to

$$\left\langle G^2 \right\rangle = \int_V \int_V B_{nn}\left(\mathbf{X}_1 - \mathbf{X}_2\right) \times \exp\left(-i\zeta\left(\mathbf{X}_1 - \mathbf{X}_2\right)\right) d\mathbf{X}_1 d\mathbf{X}_2. \qquad (30)$$

The constant coefficient of proportionality between the wave vectors $\mathbf{k}-k\mathbf{q}$ and $\boldsymbol{\zeta}$ is unimportant for further transformations, and we set it equal to unity. In the future, we will clarify its numerical value.

Meanwhile, using the Fourier spectrum, we have

$$\left\langle G^2 \right\rangle = 8\pi^3 V \int_0^{\zeta} \left(\frac{1}{8\pi^3} \int_V \exp\left(i\boldsymbol{\zeta}\mathbf{r}\right) d\mathbf{r} \right) F_{nn}(\zeta) d\zeta \approx \qquad (31)$$

$$\approx 8\pi^3 V \int_0^{\zeta} F_{nn}(\zeta) d\zeta \left(\frac{1}{8\pi^3} \int_V \exp\left(i\boldsymbol{\zeta}\mathbf{r}\right) d\mathbf{r} \right),$$

where $\mathbf{r} = \mathbf{X}_1 - \mathbf{X}_2$. The weight function:

$$f(\zeta) = \frac{1}{8\pi^3} \int_V \exp\left(i\boldsymbol{\zeta}\mathbf{r}\right) d\mathbf{r},$$

where the integral is over the entire wave space, is equal to unity [6]. Therefore, the function $f(\zeta)$ changes slightly and can be removed from the integral. The magnitude is

$$\int_0^{\zeta} F_{nn}(\zeta) d\zeta \sim \zeta^{\frac{5}{2}}$$

over a rather large range of wave vector magnitudes [8]. The mean square of the turbulence parameter $\left\langle G^2(\zeta) \right\rangle$ obeys the same law. The turbulence parameter itself obeys a law near linear $G(\zeta) \sim \zeta^{\frac{5}{4}}$, and the spectral function of turbulence approximately obeys the law $F_{nn}(\zeta) \sim \frac{d}{d\varsigma} \zeta^{\frac{5}{2}} \sim \zeta^{\frac{3}{2}}$.

Let θ be the scattering angle between the wave vector $\mathbf{k}$ of the incident electromagnetic wave and the direction $\mathbf{q}$ of the scattered wave (Fig. 2). Then, from the isosceles triangle, we obtain $\left|\mathbf{k}-k\mathbf{q}\right| = 2k\left|\sin\frac{\theta}{2}\right|$. Considering that $k = 2\pi/\lambda$, we obtain the follow value:

$$d = \frac{\lambda}{2\left|\sin\frac{\theta}{2}\right|} = \frac{2\pi}{\left|\mathbf{k}-k\mathbf{q}\right|} = \frac{2\pi}{\delta\zeta}, \qquad (32)$$

where $\delta = \left|\mathbf{k}-k\mathbf{q}\right|/\zeta$ is a parameter showing how many times $\mathbf{k}-k\mathbf{q}$ is greater than the turbulent wave vector $\boldsymbol{\zeta}$.

Eq. (32) is called the Wulff–Bragg equation for a spatial diffraction grating. The value d is an analog of the grating period, i.e., the distance between structures that scatter electromagnetic waves. Consequently, atmospheric turbulence can be represented, to some approximation, as a spatial diffraction grating.

We can assimilate the d value to the scale of turbulence. In isotropic turbulence, $d \approx 0{,}75/\zeta$ [8]. Comparison of Eq. (32) with this equation confirms the proportionality of the wave vector $\mathbf{k}-k\mathbf{q}$, i.e., the difference between the incident and turbulence-scattered electromagnetic radiation and the wave vector of the turbulent spectrum $\boldsymbol{\zeta}$. In addition, we can estimate the proportionality coefficient δ between these vectors: $2\pi/\delta = 0{,}75$ and $\delta \approx 8{,}37$ such that $\mathbf{k}-k\mathbf{q} \approx 8{,}37\boldsymbol{\zeta}$.

Conclusion

Scattering of ultrashort-wave electromagnetic radiation by atmospheric turbulence affects long-distance radio communications on ultrashort waves. The differential effective cross section for radio scattering on turbulent fluctuations of the refractive index relative to the wavelength obeys Rayleigh's law and, geometrically, a quadratic sinusoidal law with a maximum perpendicular to the original direction of radiation.

A representation of atmospheric turbulence during interaction with a radio wave as a spatial diffraction grating was revealed. The dependence of the effective period of this grating on the parameters of the electromagnetic wave and turbulence was determined.

Physically, the interaction of electromagnetic radiation and atmospheric turbulence is one of a deterministic electromagnetic wave process with a stochastic turbulent wave process. In this case, the wave vector, which characterizes the difference between the incident electromagnetic radiation and electromagnetic radiation scattered by turbulence, is proportional to the wave vector of the turbulent spectrum. The wavelength of scattered electromagnetic radiation is approximately an order of magnitude smaller than the turbulence scale.

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Некоторые особенности взаимодействия радиосигнала с турбулентной атмосферой

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Аннотация – На основе решения системы уравнений Максвелла для электромагнитного излучения в турбулентной атмосфере найдено дифференциальное эффективное сечение рассеяния этого излучения на турбулентности. Исследована зависимость сечения рассеяния от длины волны и угла рассеяния. Показано, что взаимодействие электромагнитного излучения и турбулентности атмосферы является взаимодействием детерминированного электромагнитного волнового процесса со стохастическим турбулентным волновым процессом. Отмечено, что волновой вектор рассеянного электромагнитного излучения пропорционален волновому вектору турбулентности.

Ключевые слова – турбулентность атмосферы; рассеяние электромагнитных волн; сечение рассеяния; масштаб турбулентности; Фурье-спектр турбулентности.

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