The Wave Structure Functions of Multiply Scattered Elecromagnetic Waves by Anisotropic Layer of Collisional Magnetized Turbulent Plasma

N.Kh. Gomidze, KA. Maxaradze, M.R. Xajishvili, I.S.Surmanidze, M.I.Davitadze

Batumi Satet University, Batumi, Georgia, gomidze@bsu.edu.ge

Abstract

The wave structure functions of both phase and logarithmic relative amplitude and their mutual wave structure functions are computed for two plane electromagnetic waves with different frequencies scattered by finite thickness turbulent anisotropic magnetized plasma layer in complex geometrical optics approximation using small perturbation method. Numerical calculations were carried out for F-region of an ionosphere using satellite data of ionospheric plasma parameters.

1. Introduction

Propagation and scattering of electromagnetic (EM) waves in turbulent ionospheric plasma is devoted great attention last years. Evolution of the angular power spectrum of scattered electromagnetic radiation and the features of its statistical characteristics, broadening and displacements of its maximum was investigated in geometrical optics approximation [1-4]. The effects of multiple scattering on signal statistics are very important. High-frequency monochromatic EM wave scattered on electron density fluctuations of ionospheric plasma under the action of magnetic field fluctuations lead to distortion of the observable angular power spectrum. The wave structure functions for pane, spherical waves and Gaussian beams using Rytov perturbation method have been investigated in [5-7].

In satellite communications the ability to transmit wideband data is closely related to the frequency correlation of the signals. Information about the frequency and spatial correlation of the signal is essential in designing and analyzing frequency and/or spatial diversity schemes. Therefore in this paper statistical characteristics: wave structure functions of logarithmic relative amplitude and phase fluctuations and their mutual correlation functions of frequency-spaced plane EM waves are computed using complex geometrical optics approximation taking into account the multiple scattering effects. High-frequency EM waves are scattered by anisotropic turbulent magnetized plasma layer.

2. The basic part

Let a point source is located in vacuum at a terminal distance l_1 above from the plane boundary of random magnetized plasma and irradiate high-frequency electromagnetic waves. The thickness of the scattered layer is equal to l_2 , receiver is located in vacuum below the layer at a distant l_3 in the *XZ* plane (principle plane) and the length of line-of-sight connecting the source and the receiver is $L_0 = l_1 + l_2 + l_3$. The imposed magnetic field makes an angle θ_0 between Z axis and angle θ with the direction of a wavevector of the incident wave. The plasma concentration in the layer is: $N(\mathbf{r}) = N_0 + N_1(\mathbf{r})$; where N_0 - is the constant term, $N_1(\mathbf{r})$ is a random function of the spatial coordinates describing concentration fluctuations. We shall suppose that the following inequalities are satisfied for magnetized plasma: $\omega_B >> \omega$, $\omega_B >> \nu_{eff}$, $\omega_B >> \omega_p$, where ω is the angular frequency, ν_{eff} is the effective collision frequency of electrons with other particles, $\omega_p = (4\pi e^2 N/m)^{1/2}$ is the plasma frequency and $\omega_B = eB_0/mc$ is the angular gyrofrequency for magnetic field; *e* and *m* are the charge and the mass of an electron, respectively, *c* is the speed of light in the vacuum. The plasma is considered as a uniaxial crystal having permittivity tensor components: $\tilde{\varepsilon}_{xx} = \tilde{\varepsilon}_{yy} = 1$, $\tilde{\varepsilon}_{xy} = = \tilde{\varepsilon}_{yx} = \tilde{\varepsilon}_{xz} = \tilde{\varepsilon}_{zx} = \tilde{\varepsilon}_{yz} = \tilde{\varepsilon}_{zy} = 0$, $\tilde{\varepsilon}_{zz} = 1 - \omega_p^2/(\omega^2 + i\omega\nu_{eff})$ in the coordinate system where the imposed magnetic field is directed towards the Z - axis [12].

We shall use the expansion of a spherical wave into plane waves because the theory of refraction and reflection of plane is well elaborated.

Chaotic inhomogeneities of the electron density in the plasma layer give rise to fluctuation of the wave field at the observation point. The statistical characteristics of the wave field are primarily determined by complex phase ($\tilde{\varphi}$) fluctuations of the principal plane wave in the case of small-angle scattering. The phase characteristics of an individual normal wave in the geometrical optics approximation are known [6,12] to be given by the eikonal equation $\tilde{k}^2 = \omega^2 N_*^2 / c^2$, where $\tilde{\mathbf{k}}(\mathbf{r}) = -\nabla\tilde{\varphi}$ is the local complex wavevector. The refractive index of an anisotropic medium may depend on the direction of the wavevector $N_*^2 = N_*^2(N(\mathbf{r}),\, \omega, \tilde{\mathbf{k}}_x, \tilde{\mathbf{k}}_y)$. As far as electron density fluctuations are sufficiently small $N(\mathbf{r}) = N_0 + N_1(\mathbf{r})$, $N_1 << N_0$, expand the wave phase characteristics into a series $\tilde{\mathbf{k}} = \tilde{\mathbf{k}}^0 + \tilde{\mathbf{k}}_1(\mathbf{r}) + \cdots$, $\tilde{\varphi} = \tilde{\varphi}_0 + \tilde{\varphi}_1 + \cdots$. The unperturbed wavevector $\tilde{\mathbf{k}}_0$ was obtained above without taking into account density fluctuations, using the saddle-point method, and its projection on the X axis was determined by the expression $\tilde{k}_x^0 = k_x^0$. The fluctuating terms $\tilde{\mathbf{k}}_1$ and $\tilde{\varphi}_1$ are proportional to the small dimensionless parameter N_1/N_0.

Let a point source radiates two monochromatic waves with frequencies $\omega_1 = \omega_0(1-\delta)$ and $\omega_2 = \omega_0(1+\delta)$. The value $\delta = (\omega_2 - \omega_1)/2\omega_0$ characterizes difference frequency of propagated waves. We shall calculate $<\varphi_1(\mathbf{r}_1)\varphi_2^*(\mathbf{r}_2)>$ and $<\varphi_1(\mathbf{r}_1)\varphi_2(\mathbf{r}_2)>$ for definition of frequency structure functions of phase and logarithmic relative amplitude in a plane perpendicular to a direction of propagated waves. The asterisk * means a complex conjugate. Indices 1 and 2 on the right below devoted to various frequencies. Wave structure functions of phase and logarithmic relative amplitude and their mutual correlations for two waves with different frequencies are defined by the expressions:

$$D_{\mu_1\mu_2}(\mathbf{r}_1,\mathbf{r}_2) = \frac{1}{2}\mathrm{Re}[D_1(\mathbf{r}_1,\mathbf{r}_2) + D_2(\mathbf{r}_1,\mathbf{r}_2)] \ , \tag{1}$$

$$D_{S_1S_2}(\mathbf{r}_1,\mathbf{r}_2) = \frac{1}{2}\mathrm{Re}[D_1(\mathbf{r}_1,\mathbf{r}_2) - D_2(\mathbf{r}_1,\mathbf{r}_2)] \ , \tag{2}$$

$$D_{\mu_1S_2}(\mathbf{r}_1,\mathbf{r}_2) = \frac{1}{2}\mathrm{Im}[D_2(\mathbf{r}_1,\mathbf{r}_2) - D_1(\mathbf{r}_1,\mathbf{r}_2)] , \tag{3}$$

$$D_{\mu_2S_1}(\mathbf{r}_1,\mathbf{r}_2) = \frac{1}{2}\mathrm{Im}[D_2(\mathbf{r}_1,\mathbf{r}_2) + D_1(\mathbf{r}_1,\mathbf{r}_2)] , \tag{4}$$

where structure functions of complex are

$$D_1(\mathbf{r}_1,\mathbf{r}_2) = <[\varphi_1(\mathbf{r}_1) - \varphi_1(\mathbf{r}_2)][\varphi_2^*(\mathbf{r}_1) - \varphi_2^*(\mathbf{r}_2)]> \tag{5}$$

$$D_2(\mathbf{r}_1,\mathbf{r}_2) = <[\varphi_1(\mathbf{r}_1) - \varphi_1(\mathbf{r}_2)][\varphi_2(\mathbf{r}_1) - \varphi_2(\mathbf{r}_2)]> \tag{6}$$

3. Numerical results

The following parameters are chosen for the computations: $h = 230$ km, $f = 40$ MHz, $k_0 = 0{,}83\ \mathrm{m}^{-1}$, plasma parameters: $\mathrm{v} = \omega_p^2/\omega^2 = 0.0133$, $s = \nu_{eff}/\omega = 5{,}87\cdot10^{-7}$, $l_2 = 50$ km, $l_{\|} = 10$ km, $\sigma_N^2 \approx 10^{-4}$, $l_1 = 100$ km, $l_3 = 80$ km [10,13].

Numerical calculations show that the phase correlation function broadens with increasing of both distance

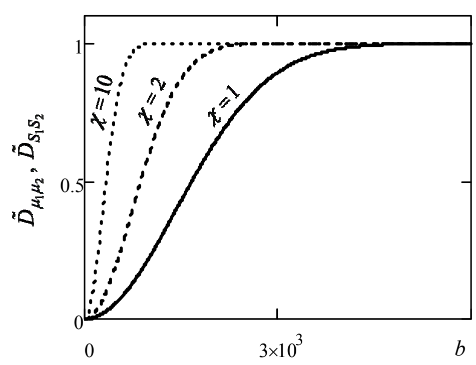

Fig.1. The dependence of normalized structure functions $\tilde{D}_{\mu_1\mu_2}$ and $\tilde{D}_{S_1S_2}$ versus nondimensional parameter b for different anisotropy parameter χ , $\alpha = 10^0$.

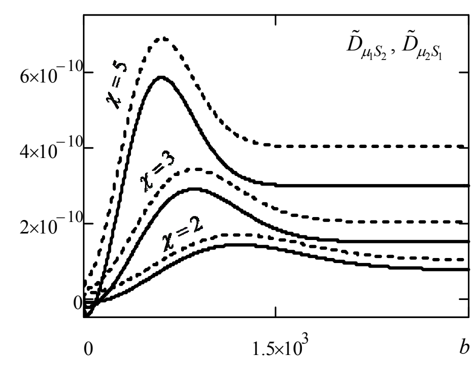

Fig.2. The dependence of normalized structure functions $\tilde{D}_{\mu_1S_2}$ (dotted lines) and $\tilde{D}_{\mu_2S_1}$ (solid lines) versus nondimensional parameter b for different anisotropy parameter χ , $\alpha = 10^0$.

between radiation point source and an upper boundary of plasma layer b and the angle α, but growth of anisotropic parameter χ, vice versa, leads to narrowing of the correlation function of phase fluctuations.

The curves of normalized structure functions versus parameter b are presented on figures 1-2 for different anisotropic parameter of electron density irregularities $\chi = (1 \div 10)$ if antennas are located on a lower boundary of turbulent plasma layer, $d = 0$; the distance between antennas is about 30 m, the length of a line-of-side is 230 km, the angles are $\theta_0 = 10^0$ and $\alpha = 10^0$.

4. Conclusions

Structure functions of phase, logarithmic relative amplitude and their mutual correlation functions of multiply scattered radiation have been obtained in complex geometrical optics approximation. The source irradiate radio waves with two different frequencies, moreover the source and observation points are located at opposite sides with respect to anisotropic turbulent magnetized plasma layer. Numerical calculations have been carried out using satellite data of F-region ionospheric plasma parameters. It was find out that anisotropy and the angle of inclination of prolate irregularities with respect to the external magnetic field have a substantial influence on the behaviour of maximums and saturation levels of these functions. The results of numerical calculations are in good agreement with satellite data.

7. References

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