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Extension of the Hybrid Scintillation Propagation Model to the Case of Field Propagation along the Magnetic Field

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ABSTRACT

As is well known, the ionospheric turbulence is highly anisotropic due to the Earth's magnetic field, and as the result, the stochastic irregularities are field aligned. Their characteristic scale in the field direction is much greater than across the field. It may even be comparable to the characteristic scale of the background ionosphere. In the description of the transionospheric stochastic channel, the case when the propagation path is oriented close to the direction of the magnetic field is a special case, and this is the subject of present consideration. The analysis performed employs the extended version of the earlier developed Hybrid Scintillation Propagation Model (HSPM) [1], which is the combination of the Complex Phase Method (CPM) [2, 3] and rigorous technique of the random (not necessarily phase) screen. In order to study the case of strongly elongated ionospheric irregularities, the CPM, which, in turn, is the extension of the classic Rytov's method to the case of the inhomogeneous background medium, was further extended to account for anisotropic random inhomogeneities of the ionospheric electron density.

When properly taking account of the anisotropic shapes of the irregularities, this results in the final representations for the field phase and log-amplitude correlation functions of more general forms, than those traditionally derived for the case of isotropic inhomogeneities. In particular, the transversal spatial spectrum for phase fluctuations is obtained in the form of the following integral:

$$F_{\chi}(\boldsymbol{\kappa}, z) = \frac{k^2}{4}\int_0^z dz' \int_{-z_m(z')}^{z_m(z')} d\zeta \left\{ \sin^2\left[\frac{\boldsymbol{\kappa}^2(z-z')}{2k}\right] - \sin^2\left[\frac{\boldsymbol{\kappa}^2\zeta}{4k}\right]\right\} F_{\varepsilon}(\boldsymbol{\kappa}, \zeta, z'). \qquad (1)$$

Here $F_{\varepsilon}(\boldsymbol{\kappa}, z_1, z_2)$ is the two-dimensional spectrum of the permittivity fluctuations, which is considered as a non-homogeneous random field in z-direction and homogeneous in the perpendicular plane, $\boldsymbol{\kappa}$ is a two-dimensional transversal spectral variable (wave number), $k = 2\pi f/c$ vacuum wave number, f is the carrier frequency. The integration limits are $z_m(z') = z - |2z' - z|$. To obtain the spectrum of the phase fluctuations coherency, the first sine should be replaced by cosine in equation (1).

In the traditional treatment of the representation in equation (1), the second item is neglected. This is correct, if the inhomogeneities are not fairly elongated. However, when they are strongly elongated (path of propagation is oriented in the direction of the Earth's magnetic field), it may give a reasonable contribution into the final result, and it should be taken into account.

When properly dealing with (1) this yields two different representations of this quantity in the domain of the transversal wave number, i.e.

$$F_{\chi,S}(\boldsymbol{\kappa},z)=\frac{\pi k^2}{4}\int_0^z dz'\left\{\Phi_\varepsilon\left(\boldsymbol{\kappa},\frac{\boldsymbol{\kappa}^2}{2k},z'\right)\mp\Phi_\varepsilon(\boldsymbol{\kappa},0,z')\cos\left[\frac{\boldsymbol{\kappa}^2(z-z')}{k}\right]\right\}, \qquad (2)$$

if the values of the transversal wave numbers $\boldsymbol{\kappa}$ satisfying the inequality $|\boldsymbol{\kappa}|z \gg l_\parallel/l_\perp$; and

$$F_S(\boldsymbol{\kappa},z)=\frac{k^2}{4}\int_0^z dz'\int_{-z_m(z')}^{z_m(z')} d\zeta\; F_\varepsilon\,(\boldsymbol{\kappa},\zeta,z') \qquad (3)$$

for small $|\boldsymbol{\kappa}|$. In the latter case $F_\chi(\boldsymbol{\kappa},z)$ is negligibly small. In equations (2) and (3) the quantities $\Phi_\varepsilon\left(\boldsymbol{\kappa},\frac{\boldsymbol{\kappa}^2}{2k},z'\right)$ and $F_\varepsilon(\boldsymbol{\kappa},\zeta,z')$ are the 3D and 2D spatial spectra of fluctuations of the dielectric permittivity correspondingly, which also depend on the slow spatial variable along the path of propagation.

To illustrate the obtained above analytical results, the numerical example is given below, where the anisotropic power law model was employed of the spectrum of the random electron density fluctuations that are not statistically homogeneous in z-direction

$$\Phi_\varepsilon(\boldsymbol{\kappa},\kappa_z,z)=a\sigma_N^2[1-\varepsilon_0^2(z)]\frac{\Gamma(p/2)}{\Gamma((p-3)/2)}\frac{1}{\pi^{3/2}\kappa_0^3}\left(1+\frac{\boldsymbol{\kappa}^2}{\kappa_0^2}+\frac{a^2\kappa_z^2}{\kappa_0^2}\right)^{-p/2}. \qquad (4)$$

Here $a=l_\parallel/l_\perp$ is the aspect ratio with $l_\parallel$ and $l_\perp$ being the outer scales of turbulence along and across the magnetic field respectively, σ_N^2 is the variance of the fractional electron density fluctuation, $\varepsilon_0(z)$ is the permittivity of the ionosphere along the reference ray in z-direction, $\kappa_0=2\pi/l_\perp$, p is the spectral index.

The plots in the Fig.1 represent the one-dimensional cuts of the two-dimensional spectra calculated employing equations (3) and (4) using the following values of main parameters: $l_\perp$=7 km, a=70, p=3.7, f=150 MHz. As is seen on the plots, the corrected spectral power density of phase and log-amplitude fluctuations deviates down from the classic power law in the "small scale" part of the spectrum corresponding to the scales less than 130 m, and the corrected phase and log-amplitude curves go lower than the classical ones.

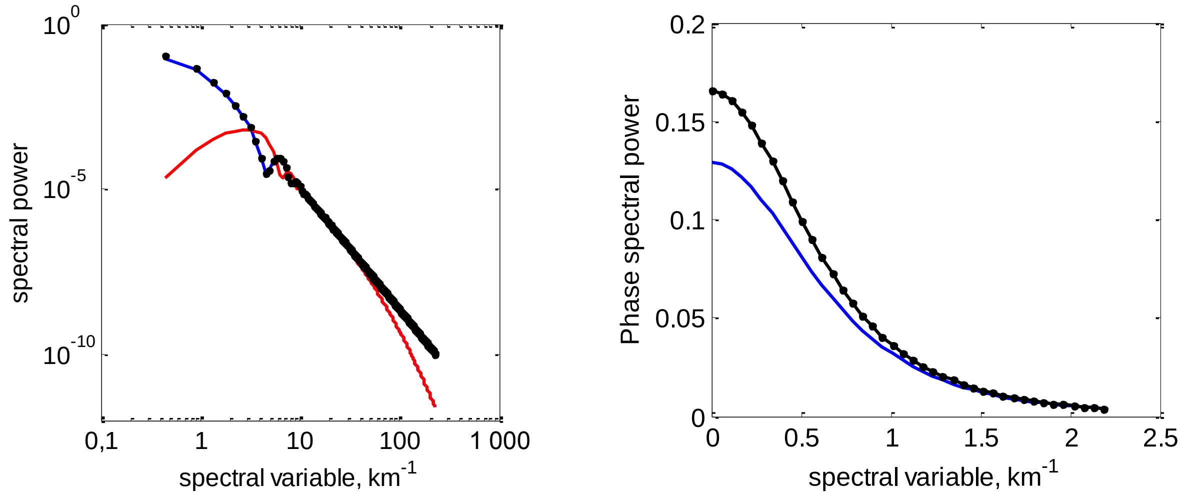

Figure 1. On the left: one-dimensional cuts of 2-D spectra of log-amplitude (red), and phase (blue) obtained utilizing (3) and (4). The black dot curve is the classical phase spectrum without corrections. On the right: the large-scale part of the phase spectra is plotted in linear scale.

This leads to the random field distributions on the screen, introduced below the ionosphere according to the HSPM technique, different of those obtained, if the effect of the anisotropy was not properly taken into account. In turn, this finally results in the values of the scintillation indices for the random field observed on the Earth's surface.

To conclude, with the results presented here incorporated into the HSPM, the new version of HSPM becomes one of a few, if not the only, semi-analytic (predominantly analytic) technique capable of self-consistently describing the realistic transionospheric stochastic channel of propagation. To utilize it, no a priori assumption respectively the type of the distribution of fluctuations of the field amplitude (intensity) is required even in the case of the field strong scintillation, generated by the HSPM for the points of observation on the Earth's surface.

Key words: Transionospheric propagation, anisotropy, scintillation, simulation.

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