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Irradiance scintillation models of plane and spherical waves considering the general distribution of anisotropic turbulence cells

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ABSTRACT

Theoretical investigations and experiments have shown the atmosphere turbulence exhibit anisotropic properties. In this work, the irradiance scintillation of optical plane and spherical waves in weak anisotropic turbulence will be investigated. Previously derived irradiance scintillation index of plane and spherical waves in weak anisotropic turbulence assumed the circular symmetric distribution of turbulence cells in the plane orthogonal to the direction of propagation. This assumption is very special for the real anisotropic turbulence. To consider the general distribution of turbulence cells in anisotropic turbulence, new expressions for the irradiance scintillation index of plane and spherical waves in weak anisotropic non-Kolmogorov turbulence have been derived with the Rytov approximation theory. In the investigations, two anisotropic factors are introduced to parameterize the asymmetric distribution of turbulence cells in anisotropic turbulence. In addition, the general spectral power law α in the range 3–4 and the finite turbulence inner and outer scales are considered in the modeling. Calculations are performed to analyze these parameters' influences on the derived irradiance scintillation index models of optical waves.

1. Introduction

The random fluctuations of atmosphere refractive-index distort the optical wave as it propagates through the atmosphere turbulence media, and a series of turbulence effects (irradiance fluctuations, angle of arrival fluctuations, and so on) will be produced. They produce non-negligible degradations to the optical communication system. For years, the theoretical modeling of atmosphere turbulence effects has been focused on the isotropic atmosphere turbulence, including the isotropic Kolmogorov turbulence ($\alpha = 11/3$) and the isotropic non-Kolmogorov turbulence ($3 < \alpha < 4$). The irradiance scintillation index models of an optical wave have been developed for optical plane, spherical, and Gaussian beam propagating through weak and moderate-to-strong isotropic turbulence [1–7]. Results indicate that the general spectral power law and finite turbulence inner scale play important roles in the derived irradiance scintillation index models. For the isotropic turbulence, the sizes of turbulence cells are assumed to be the same in different directions.

However, the turbulence can also be anisotropic at high altitudes [8–23], such as in the stratosphere, as well as on the order of meters above the ground. In this case, the turbulence cells in horizontal direction take bigger sizes than those in vertical direction. To describe the asymmetric distribution of turbulence cells in the anisotropic atmosphere turbulence, the simple turbulence refractive-index fluctuations spectral model was firstly proposed [14]. It assumed the circular symmetric

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distribution of anisotropic turbulence cells in the plane orthogonal to the direction of propagation, and is only valid in the inertial subrange. For the real anisotropic turbulence, the circular symmetric distribution of turbulence cells in the anisotropic turbulence is a special case. Also, the finite turbulence inner and outer scales are important to investigate the small-scale diffractive and large-scale refractive effects of optical waves in atmosphere turbulence media. To consider the general distribution of turbulence cells in anisotropic turbulence and the finite turbulence inner and outer scales, several improved anisotropic turbulence refractive-index fluctuations spectral models have been developed by Toselli [18,19] and Cui [21]. Of these spectral models, only the anisotropic generalized exponential spectrum and the anisotropic generalized von Karman spectrum [21] consider simultaneously the asymmetric turbulence cells in the plane orthogonal to the direction of propagation and the finite turbulence inner and outer scales.

In this work, new expressions for the irradiance scintillation index of optical plane and spherical waves will be derived for weak anisotropic turbulence. In the investigations, the anisotropic generalized exponential spectral model will be adopted. The general distribution of turbulence cells in the anisotropic turbulence, the general spectral power law and the finite turbulence inner and outer scales will be incorporated to the model establishment.

2. Anisotropic generalized exponential spectrum for atmospheric turbulence

To characterize the general distribution of turbulence cells in anisotropic turbulence and the finite turbulence inner and outer scales, the anisotropic generalized exponential spectrum was proposed as [21]:

$$\begin{aligned}&\Phi_{n\_aniso\_exp}\left(\kappa,\alpha,u_x,u_y\right)=u_x u_y\hat{A}(\alpha)\hat{C}_n^2\left(u_x^2\kappa_x^2+u_y^2\kappa_y^2+\kappa_z^2\right)^{-\alpha/2}\\&\left[1-\exp\left(-\frac{u_x^2\kappa_x^2+u_y^2\kappa_y^2+\kappa_z^2}{\kappa_0'^2}\right)\right]\exp\left(-\frac{u_x^2\kappa_x^2+u_y^2\kappa_y^2+\kappa_z^2}{\kappa_l'^2}\right).\end{aligned}\tag{1}$$

κ is the wavenumber related to the turbulence cell size, and $\kappa=\sqrt{\left(\mu_x^2\kappa_x^2+\mu_y^2\kappa_y^2\right)+\kappa_z^2}$. In which, κ_x, κ_y, and κ_z are the components of κ in the x, y, and z directions. To represent the more general distribution of turbulence cells in anisotropic turbulence, two anisotropic factors of μ_x and $\mu_y$are introduced. In the special case of $\mu_x=\mu_y$, the circular symmetric distribution of turbulence cells in the plane orthogonal to the direction of propagation is exhibited. Furthermore, when $\mu_x=\mu_y=1$, Eq. (1) reduces to the general exponential spectral model which was developed for the isotropic turbulence.

$\hat{C}_n^2=\beta C_n^2$ is generalized refractive-index structure parameter with unit $[m^{3-\alpha}]$, and β is a dimensional constant with unit $[m^{11/3-\alpha}]$. When α = 11/3, $\hat{C}_n^2$ becomes the structure parameter with unit of $m^{-2/3}$.$\hat{A}(\alpha)$ is a constant which maintains consistency between the refractive index structure function and its power spectrum, and it takes the form as

$$\hat{A}(\alpha)=\frac{1}{4\pi^2}\Gamma(\alpha-1)\cos\left[\frac{\alpha\pi}{2}\right],\tag{2}$$

In Eq. (1), κ_0' and κ_l' are the parameters related separately to the finite turbulence outer scale L_0 and turbulence inner scale l_0.

$$\kappa_0'=4\pi/L_0,\ \kappa_l'=c(\alpha)/l_0.\tag{3}$$

$c(\alpha)$ is the scaling constant with the form of

$$c(\alpha)=\left\{\pi\hat{A}(\alpha)\Gamma\left(\frac{3}{2}-\frac{\alpha}{2}\right)\left(\frac{3-\alpha}{3}\right)\right\}^{\frac{1}{\alpha-5}}.\tag{4}$$

3. Irradiance scintillation index of optical waves considering the general distribution of turbulence cells in weak anisotropic turbulence

With the Rytov approximation theory, the irradiance scintillation index of an optical wave which considers finite aperture receiver is given by [1]

$$\sigma_I^2(D)=\frac{\langle I^2\rangle}{\langle I\rangle^2}-1=4\sigma_\chi^2(D)=4\int_0^\infty B_\chi(Dx)K(x)x\,dx.\tag{5}$$

where I and$\langle I\rangle$ denote the irradiance index and the ensemble average irradiance index of optical wave at the receiver, respectively. σ_χ^2 is the log-amplitude scintillation index, D is the aperture diameter of the receiver, $B_\chi(\rho)$ represents the