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Effects of anisotropic turbulence on the long term beam spread and beam wander of Gaussian beam

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ABSTRACT

Experiments and theoretical investigations have shown that the isotropic turbulence is not the only possible turbulence in the atmosphere. Researches about the anisotropic non-Kolmogorov have attracted more and more attentions recently. In this work, the spreading and wandering of Gaussian beam under weak anisotropic turbulence are investigated. New theoretical expressions for these two kinds of turbulence effects are developed. They are observed against the variations in the effective anisotropic factor, finite turbulence inner and outer scales, and the general spectral power law. It is found that the increased effective anisotropic factor decreases the influence of anisotropic turbulence on the long term beam spread and beam wander. The increased turbulence inner scale is advantageous for decreasing the long term beam spread. While the increased turbulence outer scale is disadvantageous for alleviating the beam wander. The theoretical investigations performed in this work are helpful to better understand the optical waves' propagation under anisotropic turbulence.

1. Introduction

The statistical homogeneous and isotropic turbulence is not the only possible atmospheric turbulence. At high altitudes, such as in the stratosphere, as well as on the order of meters above the ground, the atmospheric turbulence exhibits anisotropic property [1–6]. For the anisotropic turbulence, the turbulence cells in the horizontal direction are typically bigger than those in the vertical direction. Commonly, the turbulence cells are above tens of meters in horizontal direction, while confined to a few meters in the vertical direction. This asymmetric distribution of turbulence cells in the atmosphere media plays important roles on the optical waves' propagation [1–6]. In addition, the non-Kolmogorov turbulence is the more general turbulence compared with the traditional Kolmogorov turbulence. More and more researches focused on the anisotropic non-Kolmogorov turbulence [7–14]. In this work, the spreading and wandering of Gaussian beam under weak anisotropic non-Kolmogorov turbulence will be investigated.

In the investigation of optical waves' propagation under anisotropic non-Kolmogorov turbulence, the turbulence refractive-index fluctuations spectrum, which represents the statistical distribution of turbulence cells in atmosphere turbulence media, is the most fundamental model. For the anisotropic non-Kolmogorov turbulence, the simple anisotropic non-Kolmogorov turbulence spectrum is firstly proposed [7], which takes the simplest expression but only valid in the inertial subrange. In the investigations, this spectral model is commonly extended to the whole range by assuming zero turbulence inner scale and infinite turbulence outer scale. For the real atmosphere turbulence, the turbulence inner and outer

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scales are usually with the units of millimeter and meter, respectively. In addition, just as it was investigated in the previous researches, the finite turbulence inner scale is the lower bound of turbulence cells which contribute to the diffractive effects of optical waves in atmospheric turbulence media, while the finite turbulence outer scale is the upper bound of turbulence cells which are related to the refractive effects of optical waves in atmospheric turbulence media. To consider the finite turbulence inner and outer scales, Toselli [12] extended the generalized von Karman spectrum [15] to the anisotropic non-Kolmogorov turbulence by introducing the effective anisotropic factor which can parameterize the anisotropy of turbulence cells in horizontal and vertical directions.

In this work, the analytic expressions for the long term beam spread and beam wander of Gaussian beam under weak anisotropic non-Kolmogorov turbulence will be derived. The effective anisotropic factor, the finite turbulence inner and outer scales, and the general spectral power law will be included in the theoretical modeling. Variation of these turbulence parameters on the final results will be analyzed in detail.

2. Anisotropic turbulence refractive-index fluctuations spectrum

The anisotropic turbulence refractive-index fluctuations spectral model reported in [12], introduced an effective anisotropy factor ς_{eff} to describe the asymmetric distribution of anisotropic turbulence cells. In addition, this spectral model includes the finite turbulence inner and outer scales with the form like the generalized von Karman turbulence spectral model [15]. It takes the form as [12]:

$$\Phi_n\left(\kappa,\alpha,\varsigma_{eff}\right)=\hat{A}(\alpha)\cdot\hat{C}_n^2\cdot\ \varsigma_{eff}^2\cdot\left(\varsigma_{eff}^2\kappa_{xy}^2+\kappa_z^2+\kappa_0^2\right)^{-\frac{\alpha}{2}}\exp\left(-\frac{\varsigma_{eff}^2\kappa_{xy}^2+\kappa_z^2}{\kappa_m^2}\right),\quad\left(\kappa>0,\quad 3<\alpha<4\right).\tag{1}$$

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

in which, $\kappa=\sqrt{\varsigma_{eff}^2\left(\kappa_x^2+\kappa_y^2\right)+\kappa_z^2}=\sqrt{\varsigma_{eff}^2\kappa_{xy}^2+\kappa_z^2}$, κ_x, κ_y, and κ_z are the x, y, and z components of wavenumber κ. For the non-Kolmogorov turbulence, the general spectral power law α takes the value in the range 3–4 instead of classical value of 11/3 for the Kolmogorov turbulence. $\kappa_0=2\pi/L_0$, $\kappa_m=c(\alpha)/l_0$, L_0 is the turbulence outer scale with the unit of meter, and l_0 is the turbulence inner scale with the unit of millimeter. $\hat{C}_n^2=\gamma C_n^2$ is the generalized structure parameter with unit $[m^{3-\alpha}]$, and γ is a dimensional constant with unit $[m^{11/3-\alpha}]$. $\Gamma(\cdot)$ is the gamma function. In the following analysis, by invoking the Markov approximation which assumes that the refractive index is delta-correlated at any pair of points located along the propagation direction, the z component of κ, κ_z, can be ignored. The anisotropic turbulence refractive-index fluctuations spectral model, which considers the effective anisotropic factor, the finite turbulence inner and outer scales, and the general spectral power, is reformulated as

$$\Phi_n\left(\kappa,\alpha,\varsigma_{eff}\right)=\hat{A}(\alpha)\cdot\hat{C}_n^2\cdot\ \varsigma_{eff}^2\cdot\left(\varsigma_{eff}^2\kappa^2+\kappa_0^2\right)^{-\frac{\alpha}{2}}\exp\left(-\frac{\varsigma_{eff}^2\kappa^2}{\kappa_m^2}\right),\quad\left(\kappa>0,\quad 3<\alpha<4\right).\tag{3}$$

3. Spreading of Gaussian beam under weak anisotropic turbulence

By propagating through the atmospheric turbulence media with a long distance, the intensity profile of Gaussian beam at the receiver will vary and the radius of Gaussian beam will become larger than that under no turbulence media. Suppose the diffraction limited spot radius of Gaussian beam at the receiver under no turbulence media takes the value of W, when Gaussian beam propagates through atmospheric turbulence, the beam spot size radius W_e can be expressed as [16]

$$W_e^2=\left\langle W_{LT}^2\right\rangle=W^2\left[1+T\right].\tag{4}$$

In which, the parameter T represents the amount of long term beam spread of Gaussian beam under atmospheric turbulence. In this work, the analytic expression for the long term spread of Gaussian beam under weak anisotropic non-Kolmogorov turbulence will be developed. As exhibited in [16], the long term spread of Gaussian beam under weak atmospheric turbulence is defined as [16]:

$$T=4\pi^2k^2L\cdot\int_0^1\int_0^\infty\kappa\cdot\Phi_n(\kappa)\left[1-\exp\left(-\frac{\Lambda L\kappa^2\xi^2}{k}\right)\right]d\kappa d\xi.\tag{5}$$

where $\xi=1-z/L$, L is the propagation path length, and $\Lambda=\frac{2L}{kW^2}$.

To investigate the long term spread of Gaussian beam under weak anisotropic non-Kolmogorov turbulence, the anisotropy of turbulence cell, the general spectral power law instead of classic value of 11/3, and the finite turbulence inner and outer scales will be incorporated in the modeling. In the following analysis, to simplify the derivations just as the previous