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Scintillation index of echo wave in slant atmospheric turbulence

Rui Jia, Hongyan Wei*, Hongjian Zhang, Ling Cheng, Dongmei Cai

College of Physics and Optoelectronics, Taiyuan University of Technology, No.79, Yingze West Main Street, Taiyuan 030024, Shanxi Province, China

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ABSTRACT

Scintillation effect occurs when using the corner reflector in satellite for detection of a target. The intensity fluctuation caused by atmospheric turbulence seriously affects the echo signal. This paper is to explore the influence of atmospheric turbulence and beam parameters on the scintillation index. Based on the theory of optical wave propagation in the slant path and the ITU-R turbulence structure constant model which is altitude dependent, the on-axis scintillation index of the optical wave from the transmitter to the corner reflector and from the corner reflector to the receiver is studied. Considering both inner scale and outer scale, the expression of the on-axis scintillation index of the echo wave is obtained. The relationship of the on-axis scintillation index and the Fresnel rate is calculated and analyzed with various parameters. The results show that the on-axis scintillation index is influenced by inner scale, outer scale, the wavelength and the target height.

1. Introduction

Corner reflectors, with the optical properties of reversely paralleling reflected beam and the incident beam, are mainly used in the satellite ranging, laser ranging and laser radar detection. The process of transmitting and receiving beam in these systems are divided into three links: (1) The propagation of the laser beam from the transmitter to the target of the corner reflector. The field amplitude and phase become distortion because of the atmospheric turbulence before arriving at the reflector. (2) The scattering of the incident laser by the corner reflector. (3) The propagation of the scattering laser beam from the reflector to the receiver. The following effects can be caused by the atmospheric turbulence: (1) The divergence of the incident beam. (2) The scintillation in the target plane. (3)The spread of the reflected beam. Among the influences of the atmospheric turbulence on the propagation of the laser beam, scintillation always exists and has the biggest influence on the signal distortion, greatly limiting the performance of these systems [1,2]. The beam can be approximately seen as spherical waves when arriving at the target from long distance. Therefore, it's necessary to study the scintillation index of the spherical wave reflected by the corner reflector to improve the accuracy of detection.

Light intensity scintillation refers to the phenomenon that if turbulence diameter is far smaller than the beam diameter, the section of the beam propagated in atmosphere will have many small turbulent eddies, which, respectively, scatter or diffract a small part of the incident beam. As a result, the optical power fluctuates on the receiver. Tatarski and Chemov had begun to study the optical propagation in atmospheric turbulence in the 1960s [3,4]. Rytov method made the process of calculating intensity scintillation greatly simplified and became the classic theory of dealing with the weak turbulent fluctuation. Andrews et al. extended the study to the moderate turbulence and strong turbulence using the modified Rytov method [5]. With the modified Rytov method, Wu et al. studied the optical propagation in slant atmospheric turbulence [6]. Cheng et al. described the scintillation index of the echo wave considering inner scale [7]. Cui and Cao studied the irradiance scintillation considering finite turbulence inner scale for optical wave propagating through weak non-Kolmogorov turbulence [8]. For the active optical detecting system which tends widely used, the research of the scintillation of the echo wave in the atmospheric turbulence becomes a topic issue of the current study.

Based on the theory of optical wave propagation in slant path, this paper deduced the on-axis scintillation index of the spherical wave's propagation from the transmitter to the corner reflector and back by using the atmospheric turbulence and the ITU-R turbulence structure constant model which is altitude-dependent. Considering both the inner scale and the outer scale, this paper analyzed the effect of various parameters on the scintillation index, such as inner scale, outer scale, the wavelength and the target height.

2. Beam parameters

In the optical wave propagation through the double slant path of the atmospheric turbulence, optical properties can be described by the corresponding beam parameters [9]. The non-dimensional

* Corresponding author. Tel.: +86 18635000506.
E-mail address: why_1221@126.com (H. Wei).

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curvature parameters Θ_0 and Fresnel ratio Λ_0 are introduced to describe the initial optical properties in the transmitter plane:

$$\Theta_0 = 1 - \frac{L}{F_0}, \quad \Lambda_0 = \frac{2L}{kW_0^2} \tag{1}$$

where k is the wave number, L is the distance of the slant path, W_0 is the beam radius and F_0 is the phase front radius of curvature. The incident wave on the target at $z=L$ is described by the related beam parameters:

$$\begin{aligned} \Theta_1 &= \frac{\Theta_0}{\Theta_0^2 + \Lambda_0^2} = 1 + \frac{L}{F_1} \\ \bar{\Theta}_1 &= 1 - \Theta_1 \\ \Lambda_1 &= \frac{\Lambda_0}{\Theta_0^2 + \Lambda_0^2} = \frac{2L}{kW_1^2} \end{aligned} \tag{2}$$

where W_1 and F_1, respectively, denote the radius of curvature and beam radius of the incident wave.

The reflected wave on the receiver plane can be characterized by the beam parameters:

$$\begin{aligned} \Theta_2 &= \frac{2 - \Theta_1}{\left(2 - \Theta_1\right)^2 + \left(\Lambda_1 + \Omega_R\right)^2} = 1 + \frac{L}{F} \\ \bar{\Theta}_2 &= 1 - \Theta_2 \\ \Lambda_2 &= \frac{\Lambda_1 + \Omega_R}{\left(2 - \Theta_1\right)^2 + \left(\Lambda_1 + \Omega_R\right)^2} = \frac{2L}{kW^2} \end{aligned} \tag{3}$$

where W and F, respectively, denote the radius of curvature and beam radius of the reflected wave on the receiver plane. The Fresnel ratio $\Omega_R = 2L/kW_R^2$ denotes the finite size of the reflector, where W_R is the reflector radius. Finally, the complex amplitude of the received wave is:

$$\begin{aligned} P_0 &= \Theta - j\Lambda = \left(\Theta_1 - j\Lambda_1\right)\left(\Theta_2 - j\Lambda_2\right) \\ \Theta &= \Theta_1\Theta_2 - \Lambda_1\Lambda_2 \\ \bar{\Theta} &= 1 - \Theta \\ \Lambda &= \Lambda_1\Theta_2 + \Theta_1\Lambda_2 \end{aligned} \tag{4}$$

If the incident wave is spherical, $\Theta_1 = \Lambda_1 = 0$.

3. Scintillation index of echo wave of the incident spherical wave

3.1. Atmospheric turbulence parameters

The scintillation index of the optical wave propagating through the atmosphere is mainly decided by the power spectrum of the refractive index fluctuation. For considering both the inner scale and the outer scale, we used the spectrum in literature [5]:

$$\Phi_n(\kappa) = 0.033 C_n^2\left(\xi H\right)\kappa^{-11/3} f(\kappa l_0)\, g(\kappa L_0) \tag{5}$$

where $f(\kappa l_0)$ and $g(\kappa L_0)$, respectively, denote the modified factor of the inner scale and the outer scale. They are expressed as:

$$\begin{aligned} f(\kappa l_0) &= \exp\left(-\frac{\kappa^2}{\kappa_l^2}\right)\left[1 + 1.802\frac{\kappa}{\kappa_l} - 0.254\left(\frac{\kappa}{\kappa_l}\right)^{7/6}\right] \\ g(\kappa L_0) &= 1 - \exp\left(-\frac{\kappa^2}{\kappa_0^2}\right) \end{aligned} \tag{6}$$

where $\kappa_l = 3.3/l_0$ and $\kappa_0 = 8\pi/L_0$, respectively, denote the wave number of the inner scale and the outer scale.

In Eq. (5) $C_n^2\left(\xi H\right)$ and H, respectively, are the atmospheric turbulence structure constant and the altitude of the reflector. We used the ITU-R turbulence structure constant model dependent on the altitude which is put forward by the international telecommunication [10].

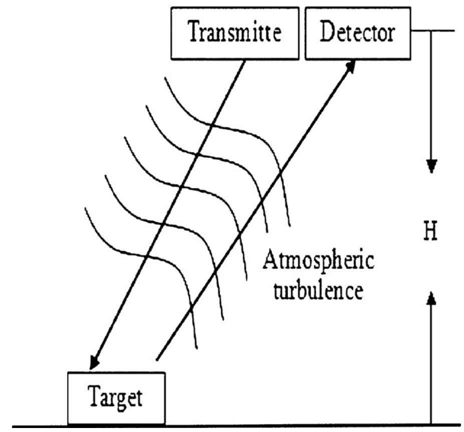

Fig. 1. Schematic for optical wave transmission with double slant path in turbulent atmosphere.

$$\begin{aligned} C_n^2\left(\xi H\right) = {} & 8.148 \times 10^{-56} \nu_{RMS}^2 \left(\xi H\right)^{10} e^{-\xi H/1000} \\ & + 2.7 \times 10^{-16} e^{-\xi H/1500} + C_0 e^{-\xi H/100} \end{aligned} \tag{7}$$

where $\nu_{RMS}^2 = \sqrt{\nu_g^2 + 30.69\nu_g + 348.91}$, ν_g and C_0, respectively, denote the wind velocity in vertical path, the wind velocity in ground layer and the atmospheric turbulence structure constant near the ground plane. Generally, the values of ν_g and C_0 are, respectively, 2.8 m/s and 1.7×10^{-14} m$^{-2/3}$.

3.2. Scintillation index of echo wave

Optical wave transmission through the double path in the atmosphere turbulence is shown as

In Fig. 1, laser beam propagates from the transmitter to the retroreflector, and echo propagates along with the same path back to the receiver. L is propagation distance in the slant path. H is the height from the target to the transmitter. Considering the double slant path between the transmitter/receiver and the target reflector, the scintillation index on the receiver plane can be expressed as [11]:

$$\sigma_I^2\left(\vec{r}, 2L\right) = \sigma_{I,b}^2\left(\vec{r}, L\right) + \sigma_{I,s}^2\left(\vec{r}, L\right) + 2C_I^{iR}\left(\vec{r}, L\right) \tag{8}$$

here $\sigma_{I,b}^2\left(\vec{r}, L\right)$ and $\sigma_{I,s}^2\left(\vec{r}, L\right)$, respectively, denote the scintillation index of the incident wave and the reflected wave. $C_I^{iR}\left(\vec{r}, L\right)$ denotes the irradiance correlation function between incident and reflected waves.

For the limiting case of the incident spherical wave, the scintillation index on the optical axis ($r=0$) reduces to:

$$\sigma_I^2(0, 2L) = 2\sigma_{I,b}^2(0, L) + 2C_I^{iR}(0, L) \tag{9}$$

The first item is described by:

$$\begin{aligned} \sigma_{I,b}^2(0, L) = {} & 8\pi^2 k^2 L \int_0^1 \int_0^\infty \kappa \Phi_n(\kappa) \exp\left(-\frac{\Lambda_2 L \kappa^2 \xi^2}{k}\right) \\ & \times \left\{1 - \cos\left[\frac{L\kappa^2}{k}\xi\left(1 - \bar{\Theta}_2\xi\right)\right]\right\} d\kappa\, d\xi \end{aligned} \tag{10}$$

where $I_0(x)$ is the modified Bessel function.