Optics Communications 330 (2014) 160–164

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Temporal spectrum of atmospheric scintillation and the effects of aperture averaging and time averaging

Hong Shen, Longkun Yu, Chengyu Fan *

Key Laboratory of Atmospheric Composition and Optical Radiation, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Hefei 230031, China

ARTICLE INFO

Article history:
Received 19 March 2014
Received in revised form
13 May 2014
Accepted 18 May 2014
Available online 2 June 2014

Keywords:
Optical turbulence
Temporal spectrum
Atmospheric scintillation

ABSTRACT

The general analytic expression for the temporal spectrum of atmospheric scintillation under weak turbulence condition is derived. It was employed to study the characteristics of the temporal spectra for horizontal uniform path and whole layer atmospheric non-uniform path. In the non-uniform path, the H-V turbulence model and the Gaussian wind speed model are utilized. It has been found that when the receiver diameter is larger than Fresnel scale $(\lambda L)^{1/2}$, the temporal spectrum of the plane wave have a power law behavior with a scaling index − 17/3 in high-frequency range. The change of the turbulence strength has little influence on the shape of the temporal spectrum. Based on the characteristics of the temporal spectrum, the aperture-averaging and time-averaging effects on scintillation were analyzed in the frequency domain.

1. Introduction

Atmospheric scintillation, one of the most important turbulence effects when optical beam propagates through atmosphere, has a strong impact on performance of the free-space optical (FSO) communication system [1–4]. In order to reduce the influence of atmospheric scintillation, aperture-averaging and time-averaging have been widely used in the detection system for FSO communication [1,5,6]. Acquisition-pointing-tracking (APT) subsystem employs time-averaging to diminish the fade budget, while communication subsystem utilizes aperture-averaging to improve signal-to-noise ratio and reduce bit-error-rate. Temporal spectrum or power spectral density (PSD) of atmospheric scintillation is one of the main characteristics of atmospheric noise associated with optical communication systems and laser radar systems [1]. Knowledge of PSD of atmospheric scintillation can provide guidance for engineering design and performance evaluation of the FSO system employed in the atmosphere. For example, in an FSO link with high-speed digital data transmission up to several gigabits per second, a deep and long-term fading in optical intensity results in considerable burst errors in the data. In compensating the intensity fluctuations by using the automatic gain control (AGC) function of an optical amplifier at an optical receiver side, slower response speed of the AGC causes degradation in the link performance [7]. For temporal spectrum of atmospheric scintillation, most literature focus on either the ideal horizontal path with constant turbulence strength and wind speed [8–10] or the whole layer atmospheric path with Rms (root mean square) wind instead of the real wind [11], but consideration of turbulence and wind speed fluctuations in real paths have been rarely reported.

Based on the Kolmogorov power-law spectrum and Taylor frozen turbulence hypotheses, we have theoretically deduced the general analytic expression for the temporal spectrum of the atmospheric scintillation under weak turbulence condition in Section 2, numerically investigated the characteristics of the PSD of atmospheric scintillation for different propagation scenarios in Section 3, and also analyzed the aperture-averaging and time-averaging effects in the frequency domain based on the known characteristics of the temporal spectrum in Section 4. We finally summarize the conclusions in Section 5.

2. Temporal spectrum

In many cases, the relationship of normalized irradiance variance (scintillation index) and log-amplitude variance on an aperture can be expressed as [12,13,16]

$$\frac{\sigma_S^2}{\overline{S}^2} = \exp\left[4\sigma_A^2\right] - 1, \tag{1}$$

where S represents the irradiance collected by an aperture, and A is the log-amplitude on the aperture. In general, the irradiance fluctuation of the optical wave propagating through atmosphere is defined

* Corresponding author.
E-mail address: cyfan@aiofm.ac.cn (C. Fan).

http://dx.doi.org/10.1016/j.optcom.2014.05.039
0030-4018/

as atmospheric scintillation. Because the irradiance fluctuation is essentially the log-amplitude fluctuation, the log-amplitude fluctuation is also called as atmospheric scintillation [14]. The temporal spectrum of atmospheric scintillation discussed here refers to the temporal spectrum of log-amplitude fluctuations, and according to Eq. (1), we know that the characteristics of the temporal spectrum of log-amplitude fluctuations can be used to study the characteristics of irradiance fluctuations. Under weak turbulence condition, utilizing the analytical approach developed by Sasiela [14], covariance function of log-amplitude fluctuations can be derived as

$$B_A(\rho)=0.132\pi^2k^2\int_0^L dzC_n^2(z)\int_0^\infty J_0(\kappa\gamma\rho)\kappa^{-8/3}\sin^2\left(\frac{\kappa^2\gamma z}{2k}\right)F(\gamma\kappa)d\kappa \tag{2}$$

In Eq. (2), the observation plane is taken at the coordinate origin $z=0$, ρ is the spatial distance, k is the optical wave number, C_n^2 is the refractive-index structure parameter [1,8,14], L is the propagation distance, κ is the spatial wave number, J_0 is the first kind Bessel function of order zero, γ is the propagation parameter that has complex value for beam waves of finite extent, and has the simple value in the two limiting case $\gamma=1$for plane waves, and $\gamma=1-z/L$ for spherical waves, $F(\gamma\kappa)$ is the aperture filter function and has the form [1,14]

$$F(\gamma\kappa)=\left[\frac{2J_1(\kappa\gamma D/2)}{\kappa\gamma D/2}\right]^2, \tag{3}$$

for circular aperture with diameter D, where J_1 is the first kind Bessel function of order one.

Using Taylor frozen turbulence hypothesis, the covariance function of log-amplitude fluctuations in temporal domain can be obtained as

$$B_A(\rho,\tau)=0.132\pi^2k^2\int_0^L dzC_n^2(z)\int_0^\infty J_0(\kappa(\gamma\rho-v(z)\tau))\kappa^{-8/3}\sin^2\left(\frac{\kappa^2\gamma z}{2k}\right)F(\gamma\kappa)d\kappa, \tag{4}$$

where τ is the lag time, $v(z)$ is the crosswind speed (i.e. the wind speed perpendicular to the path) at position z. For a single receiver ($\rho=0$), taking the Fourier transform of Eq. (4), the temporal spectrum of log-amplitude fluctuations, or power spectral density (PSD) $W_A(f)$, can be written as

$$W_A(f)=0.528\pi^2k^2\int_0^L dzC_n^2(z)\int_{\frac{2\pi f}{v(z)}}^\infty[(\kappa v(z))^2-(2\pi f)^2]^{-1/2}\kappa^{-8/3}\sin^2\left(\frac{\kappa^2\gamma z}{2k}\right)F(\gamma\kappa)d\kappa. \tag{5}$$

Integrating the power spectral density over all frequencies gives the log-amplitude variance, that is $\sigma_A^2=\int W_A(f)df$. From Eq. (5), it can be seen that the temporal spectrum is a turbulence integral parameter that relates to the crosswind speed on the path and receive aperture size and propagation parameter. To provide a foundation for understanding the characteristics of the temporal spectra, we first analyze the path-weighting function of $W_A(f)$, i.e. the last integral of Eq. (5). The path-weighting function can be split into four parts: the wind speed term $[(\kappa v(z))^2-(2\pi f)^2]^{-1/2}$, the turbulence spectrum term $\kappa^{-8/3}$, the amplitude term $\sin^2(\kappa^2\gamma z/2k)$ and the aperture filter function $F(\gamma\kappa)$. It can be seen that, the wind speed term indicates turbulent eddy with $\kappa=2\pi f/v$ which contributes the most to the PSD, turbulent eddies with $\kappa<2\pi f/v$ are cut off, and make no contribution to the PSD; the turbulence spectrum term denotes that eddies with small wave number (large-sized eddies) contributes more to the PSD. From the amplitude term one can deduce that the most effective κ is $2\pi(2n+1/2\lambda\gamma z)^{1/2}$ (n is the natural number), corresponding to the eddy size $(2\lambda\gamma z/(2n+1))^{1/2}$, which means the scale of the eddy that contributes more varies with its location; Filter function $F(\gamma\kappa)$ is a low-pass filter function that passes contribution from low κ and attenuates contribution from high κ. To sum up, we can obtain some qualitative conclusions that turbulent eddy with Fresnel scale $(\lambda L)^{1/2}$ contributes the most to the PSD; when the frequency is greater than the corner frequency [8] ($f>v/(\lambda L)^{1/2}$), the PSD drops rapidly since those turbulent eddies with small κ that contribute the most is not involved in the integral. Due to the complexity of the formula, we study the characteristics of the temporal spectrum through a numerical method to obtain some quantitative descriptions.

Notice that in this paper we only consider the plane wave and spherical wave limiting cases, for a collimated Gaussian beam with $1/e$ field radius w_0 with a Fresnel ratio of $\Lambda_0=2L/(kw_0^2)$, it is not easy to evaluate the PSD of log-amplitude fluctuations for the complex value of propagation parameter γ. Andrews and Phillips [1] show that the general behavior of PSD for beam waves is similar to that for the plane wave and spherical wave limiting cases and call beams with $\Lambda_0>100$ approximately spherical and $\Lambda_0<0.01$ approximately planar . Therefore, Eq. (5) for plane wave model is applicable for a beam wave with $\Lambda_0<0.01$ often occurred in a downlink channel, and Eq. (5) for spherical wave model is applicable for a beam wave with $\Lambda_0>100$ often occurred in an uplink channel.

3. Numerical results of temporal spectrum

3.1. Horizontal path

To explore the general characteristic of the temporal spectrum for horizontal path with uniform turbulence strength and wind speed, we calculated the PSD of scintillation with a point receiver for a range of wind speeds for the plane wave, as shown in Fig. 1. $L=1$ km, $C_n^2=1.7\times10^{-14}\,\text{m}^{-2/3}$, $\lambda=632$ nm, and wind speed of 0.5, 1, 3 m/s were adopted in the calculation. We selected those typical calculation parameters and made sure that weak turbulence condition (log-amplitude variance less than 0.35 [14]) is satisfied. From Fig. 1 it can be seen that, for a point receiver, the temporal spectrum for plane waves has a corner frequency $f_c=v/(\lambda L)^{1/2}$.
In the low-frequency range ($f<f_c$), it is nearly constant; in the high-frequency range ($f>f_c$), it obeys the power law with an exponent of $-8/3$. When the wind speed increases, the corner frequency becomes large. High frequency proportion increases while low frequency proportion descends to keep the integral over the whole frequency domain (i.e. the area under the power spectrum) constant, which means that the wind speed does not affect the scintillation value. These spectral characteristics are consistent with the former literature [8–10].

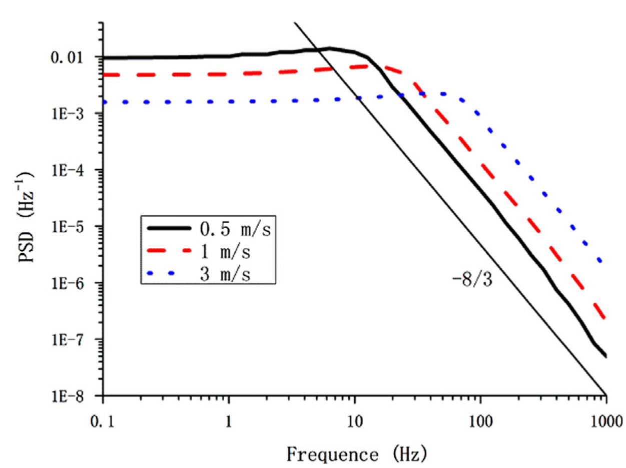

Fig. 1. Power spectra of scintillation of plane waves with a point receiver for a range of wind speeds in horizontal path.