Optik 144 (2017) 553–560

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Strehl ratio and spread rate of Gaussian–Schell model beams in the marine–atmosphere link of weak to strong scintillations

Qiu Wang[a], Beibei Hu[a], Lin Yu[a,b], Yixin Zhang[a,b,*]

[a] School of Science, Jiangnan University, Wuxi 214122, China
[b] Jiangsu Provincial Research Center of Light Industrial Optoelectronic Engineering and Technology, Wuxi 214122, China

ARTICLE INFO

Article history:
Received 4 January 2017
Received in revised form 17 April 2017
Accepted 28 June 2017

Keywords:
Strehl ratio
Spread rate
Weak to strong scintillation
Marine–atmosphere
Slant path

ABSTRACT

We present the models of the Strehl ratio (SR) and the spread rate of Gaussian–Schell model (GSM) beams in the long slant path of marine–atmosphere turbulence. The models are developed based on the extended Rytov theory which permits us extending the results of weak scintillation into the moderate-to-strong scintillation regimes. Our results show that there exists a minimum of SR for selected waist radiuses and the minimum SR is dependent on the transverse coherent width of light source. The spread rate increases with increasing the light wavelength but it decreases with increasing the waist radius and the inner scale. The effects of turbulence on the peak received irradiance can be reduced by selecting larger waist radius of transmitting aperture and longer light wavelength.

1. Introduction

The propagation of laser beams through atmospheric turbulence has been the subject of much study because it is very important for many practical applications, such as remote sensing, imaging, atmospheric optical communication, etc. Air turbulence includes terrestrial atmospheric turbulence, maritime atmospheric turbulence, turbulent heated jet and so on. It is known that turbulence affects the properties of the beam in air, e.g., beam broadening beyond natural diffraction effects, degree of polarization, degree of coherence fluctuations [1,2], the spiral spectrum of the orbital angular momentum carried by vortex beams [3,4], the kurtosis parameter [5], and phase fluctuations [6,7]. In the terrestrial atmospheric turbulence link, for characterizing the optical antenna performance as a function of turbulence conditions, the most commonly used metric is the SR [8,9], a parameter borrowed from the astronomy field [10]. SR provides a measure of the on-axis intensity relative to a diffraction limited beam [10]. It is commonly used for characterizing the compensation performance of a receive aperture for adaptive optics system by evaluating signals at the focal plane [11,12] and evaluating the beam quality in inter-satellite laser communications [13]. The SR metric can also be applied to transmit apertures to characterize the pre-compensation performance in the far-field, for example, at the plane of the receive aperture [14]. The study of partially coherence apertured beams in turbulence shows that the SR of these beams decreases with the increasing beam coherence parameter and truncation parameter [15]. The effect of scintillation on turbulence-induced centroid anisoplanatism on the resulting SR can be negligible [16]. More recently, SR of the (GSM) vortex beams and GSM non-vortex beams propagation

* Corresponding author at: School of Science, Jiangnan University, Wuxi 214122, China.
E-mail address: zyx@jiangnan.edu.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.ijleo.2017.06.116

through non-Kolmogorov atmospheric turbulence were derived [17]. For turbulent heated jet, J.M. Cicchiello and E.J. Jumper studied the degradation of the time-averaged SR [18]. We know that maritime atmospheric turbulence is different from terrestrial atmospheric turbulence because of their different environments [19–22]. However, to the best of our knowledge, the SR is limited to regimes of weak irradiance scintillation near the sea level [23]; there are no reports about the effects of the long slant path and moderate to strong maritime scintillations on the SR and the spread rate of GSM beams. But, in the practical optical communication between islands and planes, we face a long path communication, so the study of the effect of the long slant path and moderate to strong maritime scintillations on the SR and the spread rate of GSM beams is very necessary.

In this paper, we develop the models of the SR and spread rate for GSM beams propagation in the weak to strong scintillation link of marine–atmosphere based on the extended Rytov theory. The paper is organized as follows, in Section 2, we develop the long-term spreading equation, SR and spread rate model for beams propagation in the slant turbulent link of marine–atmosphere. In Section 3, based on the geometrical optics approximation, we develop SR and spread rate of collimated beams in weak to strong scintillations. Numerical results and analysis are given in Section 4, and conclusions are given in Section 5.

2. Strehl ratio and spread rate of GSM beams in weak to strong scintillations

A useful parameter to evaluate optical system performance is the SR which is defined as the ratio between the peak irradiance received by an optical system propagating in turbulence $\langle I(0,z)\rangle$, and the peak irradiance without propagation in atmospheric turbulence $I^0(0,z)$. It is considered that the SR of a beam close to unity (zero) can be considered having a good (bad) quality. The irradiance is related to the spot size of the beam, therefore the SR can be written as [10,24]

$$\mathrm{SR}=\frac{\langle I(0,z)\rangle}{I^0(0,z)}\cong\frac{w^2(z)}{w_L^2(z)}, \tag{1}$$

where $w_L(z)$ is the long-term beam spreading, $w(z)=[w_0^2+4z^2(1/w_0^2+1/\rho_{s0}^2)/k^2]^{1/2}$ [22] is the free-space beam radius at the distance z, w_0 is the waist radius of GSM beams, ρ_{s0} is the transverse coherent width of the source. The SR expressed by Eq. (1) describes the beam spreading caused by turbulence.

According to the first-order weak-fluctuation Rytov theory, the long-term beam spreading is given by [1,24]

$$w_L(z)=w(z)[1+T(z)]^{1/2}, \tag{2}$$

with

$$T(z)=4\pi^2k^2\int_0^z\int_0^\infty\varphi_n(\kappa)\left[1-\exp\left(-\frac{2z^2\kappa^2\zeta^2}{k^2w^2(z)}\right)\right]\kappa\,\mathrm{d}\kappa\,\mathrm{d}\xi, \tag{3}$$

where $k=2\pi/\lambda$ is the wave number with being the wavelength, $\varphi_n(\kappa)$ is the spatial spectrum of refractive-index fluctuation, κ is the spatial wave number, ξ is the distance of an intercept point from the input plane at $\xi=0$ and $\zeta=1-\xi/z$.

According to Eqs. (2), (3) and (1), the SR of the weak scintillation is given by [24]

$$SR=\frac{1}{1+T(z)}. \tag{4}$$

Based on the extended Rytov theory [1,24] that extend weak fluctuation results into weak to strong scintillation regimes, the factor $T(z)$ in Eq. (2) can be extended as

$$T_{eff}(z)=4\pi^2k^2\int_0^z\int_0^\infty\varphi_{eff}(\kappa)\left[1-\exp\left(-\frac{2z^2\kappa^2\zeta^2}{k^2w^2(z)}\right)\right]\kappa\,\mathrm{d}\kappa\,\mathrm{d}\xi, \tag{5}$$

where $T_{eff}(z)$ is valid in the weak to strong scintillation regimes, $\varphi_{eff}(\kappa)=\varphi_{nx}+\varphi_{ny}$, is the effective spatial spectrum of refractive-index fluctuations that is applicable in weak-to-strong fluctuation regimes, and φ_{nx} and φ_{ny} are the spatial spectrum of refractive-index fluctuations associated with large-scale and small-scale effects.

From Eq. (5), we obtain the long-term beam spreading which is corresponding to weak-to-strong scintillations

$$w_{L,eff}(z)=w(z)[1+T_{eff}(z)]^{1/2}. \tag{6}$$

For marine–atmosphere [21,22] and by extended Rytov theory [1,25], the effective spatial spectrum of refractive-index scintillation is given by

$$\varphi_{eff}=0.033C_n^2(h)\kappa^{-11/3}[f_H(\kappa l_0)g(\kappa L_0)G_x(\kappa)+G_y(\kappa)], \tag{7}$$

where $C_n^2(h)$ is the refractive index structure constant with units $m^{-2/3}$, $L_0(h)=5/\{1+\left[(h-7500)/2000\right]^2\}$ is the outer scale of turbulence(h is the altitude) [26], $g[\kappa L_0(h)]=\kappa^{11/3}(\kappa^2+\kappa_0^2)^{-11/6}$ describes outer-scale effects with $\kappa_0=2\pi/L_0(h)$ and $f_H(\kappa l_0)=\exp(-\kappa^2/\kappa_H^2)[1-0.061\kappa/\kappa_H+2.836(\kappa/\kappa_H)^{7/6}]$ describes inner-scale effects with $\kappa_H=3.41/l_0$ (l_0 is the inner