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Flat-topped Gaussian laser beam scintillation in weakly turbulent marine atmospheric medium

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ABSTRACT

In a weakly marine turbulent medium, formulation of the on-axis scintillation index of a flat topped Gaussian beam is derived by using the Rytov method and the intensity has log-normal distribution expressed. The scintillation index and average bit error rate < BER > with respect to changes in propagation distance, wavelength, beam size, and average signal to noise ratio < SNR > are exhibited. Our results indicated that small < BER > advantage can be achieved in weak atmospheric marine when focal length equals to propagation distance and when the order of flatness is small value.

1. Introduction

A marine layer is an air mass existing over the surface of a huge body of water, such as the ocean or a large lake. In this part of the atmosphere, the humidity increases gradually through the evaporation of the water in the ocean or lake surface and because of the presence of a large amount of heat. The marine layer is a very important factor in the design of the laser detection and ranging (LADAR) and optical communication system [1–3]. Atmosphere has many effects on the propagation of optical waves, and atmospheric turbulence has one of the most important effects because it reduces the performance of optical communication systems. The main effect of atmospheric turbulence is scintillation. Thus, many researchers are interested in determining which particular special beams contributing to the reduction of the degrading effects in atmospheric turbulence; however, few of these works are related to marine turbulence [4–10]. This paper predominantly focuses on the effect of using flat-topped Gaussian laser beams as excitation on the scintillation index of atmospheric marine. We present only the relevant literature for using flat topped beams as excitation. The characteristic of the scintillation of both partially coherent annular and flat-topped array beams when utilized in tremendously strong turbulent atmosphere are investigated in [11]. The behavior of the intensity fluctuations when a realistic receiver with a finite dimension aperture is employed in an atmospheric optics link is explored through the use of flat-topped beams in a previous study [12]. Another study focused on the average bit error rate (BER) of multi-Gaussian beams in non-Kolmogorov weak turbulence for every distinctive incidence of annular and flat-topped optical.

beams [13]. In [14], the average BER of annular and flat-topped beams in strong turbulence are estimated. Meanwhile, the plane characteristics of the source and receiver of flat-topped beams propagating in turbulent atmosphere are scrutinized in [15]. The behavior of intensity fluctuations of flat-topped beams when they propagate in atmospheric turbulence governed by the non-Kolmogorov spectrum is investigated in [16]. In [17], the intensity distribution of flat-topped beam in a turbulent atmosphere for a balloon satellite with various zenith angles is examined. The scintillation index is calculated for a flat-topped Gaussian beam source in atmospheric turbulence in [18]. In a strongly turbulent medium, the on-axis scintillation index of flat-topped Gaussian beams is formulated and evaluated in [19]. In this paper, we examined the scintillation index for a flat-topped Gaussian beam in weak marine turbulence with horizontal link. Our goal is to explore suitable incidence field profiles that reduce scintillations and improve the performance of optical communication system.

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2. Formulation

The on-axis scintillation index of flat-topped Gaussian beams in weak turbulence at the receiver plane is as follows [19]:

$$m^2 = 4\pi Re\left\{\int_0^L d\eta \int_0^\infty \kappa d\kappa \int_0^{2\pi} d\theta [F1(\eta,\kappa,\theta) + F2(\eta,\kappa,\theta)]\Phi_n(\kappa)\right\}, \quad (1)$$

here, Re represents the real part,η is the variable for the distance along the propagation axis, (κ, θ) refers to the polar coordinate representation of the two-dimensional spatial frequency, L is the link length, and $\Phi_n(\kappa)$is the spectral density of the index of refraction fluctuations

$$\begin{aligned} F1(\eta,\kappa,\theta) = & -k^2 M^{-2}(L)\sum_{n_1=1}^{N}\sum_{n_2=1}^{N}(-1)^{n_1+n_2}(1+i\alpha_{n_1}L)^{-1} \\ & \times (1+i\alpha_{n_2}L)^{-1}\binom{N}{n_1}\binom{N}{n_2} \\ & \times exp(-0.5 \quad k^{-1} \quad i(L-\eta)(1+i\alpha_{n_1}\eta) \\ & \times exp(-0.5 \quad k^{-1} \quad i(L-\eta)(1+i\alpha_{n_2}\eta)(1+i\alpha_{n_2}L)^{-1}\kappa^2), \end{aligned} \quad (2)$$

$$\begin{aligned} F2(\eta,\kappa,\theta) = & \ k^2 |M(L)|^{-2}\sum_{n_1=1}^{N}\sum_{n_2=1}^{N}(-1)^{n_1+n_2}(1+i\alpha_{n_1}L)^{-1} \\ & \times (1-i\alpha_{n_2}L)^{-1}\binom{N}{n_1}\binom{N}{n_2} \\ & \times exp(-0.5 \quad k^{-1} i(L-\eta)(1+i\alpha_{n_1}\eta)(1+i\alpha_{n_1}L)^{-1}\kappa^2) \\ & \times exp(0.5 \quad k^{-1} i(L-\eta)(1-i\alpha_{n_1}\eta)(1-i\alpha_{n_2}L)^{-1}\kappa^2), \end{aligned} \quad (3)$$

$$M(\mathrm{L}) = \sum_{n=1}^{N}(-1)^{n-1}\binom{N}{n}(1+\mathrm{i}\alpha_n \mathrm{L})^{-1}, \quad (4)$$

where $i=(-1)^{0.5}$,$\alpha_n = 1/k\alpha_{sn}^2 = n/k\alpha_s^2$, $\alpha_{sn} = \alpha_s/\sqrt{n}$represents the source size of the nth beam, $k = 2\pi/\lambda$ is the wave number, λ is the wavelength, and N is the number of Gaussian beams that comprise the flat-topped Gaussian incident field which is expressed as [19]:

$$\mathrm{u(s)} = \sum_{n=1}^{N}\frac{(-1)^{n-1}}{N}\binom{N}{n}exp\left\{-n\left(s_x^2+s_y^2\right)/2\alpha_s^2\right\}, \quad (5)$$

where $s = (s_x, s_y)$ is the source transverse coordinate. The marine atmospheric spectrum is as follows [2,3]:

$$\Phi_n(\kappa) = 0.033Cn^2k^2\left[1 - 0.061\frac{\kappa}{\kappa_H} + 2.836\frac{\kappa^{7/6}}{\kappa_H^{7/6}}\right]\frac{\exp(-\kappa^2/\kappa_H^2)}{(\kappa_0^2+\kappa^2)^{11/6}} \quad , \quad (6)$$

where $\kappa_H = 3.14/l_0$, $\kappa_0 = 1/L_0$, the inner and outer scales of turbulence l_0 and L_0, C_n^2 is the refractive index structure parameter, and κ denotes the spatial wave number which is valid for $0 \le \kappa < \infty$. Inserting Eqs. (2, 3, 4, and 6) into Eq. (1), after rearranging, the integral over κ can be solved using Eqs. 1.211–3 and 3.241–4 from [20]. After solving the integral over κ and simplifying, the equation becomes

$$\begin{aligned} m^2 = 1.39k^2Cn^2Re & \Bigg\{\Bigg\{\Bigg[\int_0^L d\eta \sum_{n_1=1}^{N}\sum_{n_2=1}^{N}\sum_{n=0}^{\infty}\frac{1}{n!}\frac{(-1)^{n_1+n_2}}{(1+i\alpha_{n_1}L)(1+i\alpha_{n_2}L)}\binom{N}{n_1}\binom{N}{n_2} \\ & \times \frac{-1}{M^2(L)}\left[-\frac{i(L-\eta)}{2k}\frac{(1+i\alpha_{n_1}\eta)}{(1+i\alpha_{n_1}L)} - \frac{i(L-\eta)}{2k}\frac{(1+i\alpha_{n_2}\eta)}{(1+i\alpha_{n_2}L)} - \frac{1}{\kappa_H^2}\right]^n \\ & + \frac{1}{|M(L)|^2}\int_0^L d\eta \sum_{n_1=1}^{N}\sum_{n_2=1}^{N}\sum_{n=0}^{\infty}\frac{1}{n!}(-1)^{n_1+n_2}\binom{N}{n_1}\binom{N}{n_2} \\ & \times \frac{1}{(1+i\alpha_{n_1}L)(1-i\alpha_{n_2}L)}\left[-\frac{i(L-\eta)}{2k}\frac{(1+i\alpha_{n_1}\eta)}{(1+i\alpha_{n_1}L)} + \frac{i(L-\eta)}{2k}\frac{(1-i\alpha_{n_2}\eta)}{(1-i\alpha_{n_2}L)} - \frac{1}{kH^2}\right]^n\Bigg] \\ & \times (\kappa_0^2)^{n-\frac{5}{6}}\Gamma\left(-n+\frac{5}{6}\right)\Gamma(n+1)\Bigg\} \\ & - \frac{0.061}{\kappa_H}\Bigg\{\Bigg[\int_0^L d\eta \sum_{n_1=1}^{N}\sum_{n_2=1}^{N}\sum_{n=0}^{\infty}\frac{1}{n!}\frac{(-1)^{n_1+n_2}}{(1+i\alpha_{n_1}L)(1+i\alpha_{n_2}L)}\binom{N}{n_1}\binom{N}{n_2} \\ & \times \frac{-1}{M^2(L)}\left[-\frac{i(L-\eta)}{2k}\frac{(1+i\alpha_{n_1}\eta)}{(1+i\alpha_{n_1}L)} - \frac{i(L-\eta)}{2k}\frac{(1+i\alpha_{n_2}\eta)}{(1+i\alpha_{n_2}L)} - \frac{1}{\kappa_H^2}\right]^n \\ & + \frac{1}{|M(L)|^2}\int_0^L d\eta \sum_{n_1=1}^{N}\sum_{n_2=1}^{N}\sum_{n=0}^{\infty}\frac{1}{n!}(-1)^{n_1+n_2}\binom{N}{n_1}\binom{N}{n_2} \\ & \times \frac{1}{(1+i\alpha_{n_1}L)(1-i\alpha_{n_2}L)}\left[-\frac{i(L-\eta)}{2k}\frac{(1+i\alpha_{n_1}\eta)}{(1+i\alpha_{n_1}L)} + \frac{i(L-\eta)}{2k}\frac{(1-i\alpha_{n_2}\eta)}{(1-i\alpha_{n_2}L)} - \frac{1}{\kappa_H^2}\right]^n\Bigg] \\ & \times (\kappa_0^2)^{n-\frac{1}{3}}\Gamma\left(-n+\frac{1}{3}\right)\Gamma\left(n+\frac{3}{2}\right)\Bigg\} \\ & + \frac{2.836}{\kappa_H^{7/6}}\Bigg\{\Bigg[\int_0^L d\eta \sum_{n_1=1}^{N}\sum_{n_2=1}^{N}\sum_{n=0}^{\infty}\frac{1}{n!}\frac{(-1)^{n_1+n_2}}{(1+i\alpha_{n_1}L)(1+i\alpha_{n_2}L)}\binom{N}{n_1}\binom{N}{n_2} \\ & \times \frac{-1}{M^2(L)}\left[-\frac{i(L-\eta)}{2k}\frac{(1+i\alpha_{n_1}\eta)}{(1+i\alpha_{n_1}L)} - \frac{i(L-\eta)}{2k}\frac{(1+i\alpha_{n_2}\eta)}{(1+i\alpha_{n_2}L)} - \frac{1}{\kappa_H^2}\right]^n \\ & + \frac{1}{|M(L)|^2}\int_0^L d\eta \sum_{n_1=1}^{N}\sum_{n_2=1}^{N}\sum_{n=0}^{\infty}\frac{1}{n!}(-1)^{n_1+n_2}\binom{N}{n_1}\binom{N}{n_2} \\ & \times \frac{1}{(1+i\alpha_{n_1}L)(1-i\alpha_{n_2}L)}\left[-\frac{i(L-\eta)}{2k}\frac{(1+i\alpha_{n_1}\eta)}{(1+i\alpha_{n_1}L)} + \frac{i(L-\eta)}{2k}\frac{(1-i\alpha_{n_2}\eta)}{(1-i\alpha_{n_2}L)} - \frac{1}{\kappa_H^2}\right]^n\Bigg] \\ & \times (\kappa_0^2)^{n-\frac{1}{4}}\Gamma\left(-n+\frac{1}{4}\right)\Gamma\left(n+\frac{19}{12}\right)\Bigg\}\Bigg\}. \end{aligned} \quad (7)$$

To verify the accuracy of our model, we reduce Eq. (8) to Gaussian beam scintillation by using flatness order, must be (N=1). Then, when inner scale l_0=0 and neglect the impact of outer scales because the outer scale of turbulence has a negligible impact on the scintillation index in weak fluctuations; however its effect starts to appear as the strength of the fluctuations increases [2,21]. The equation correctly reduces to the Known Gaussian beam scintillation index in Kolmogorov spectrum, which is matches Gaussian beam scintillation in Kolmogorov in [18].

In weak marine turbulence, the average BER is given as follows [21]:

$$<BER> = 0.5\int_0^\infty P_I(u)erfc\left(u\frac{<SNR>}{2\sqrt{2}}\right)du, \quad (9)$$

where $<SNR>$ is the average signal-to-noise ratio, $erfc$ (.) is the complementary error function, u is the normalized signal with unity