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Beam wander of laser beam propagating through oceanic turbulence

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ABSTRACT

The analytical expressions for beam wander of collimated and focused beam in oceanic turbulence are derived. Compared with the previously integrating ones, it can be seen that the two results are in agreement with each other exactly for the collimated and focused beam, respectively. Further, the influences of three main oceanic parameters (i.e., the rate of dissipation of mean-squared temperature χ_T, the rate of dissipation of kinetic energy per unit mass of seawater ε and the ratio of temperature to salinity contribution to the refractive index spectrum w) and the beam radius W_0 on beam wander are investigated in the collimated and focused beam cases. The results indicate that the beam wander increases as ε decreases, χ_T increases, salinity-induced predominates and W_0 decreases in mentioned above cases. In addition, based on the dimensionless quantity B_W, the relation between beam wander and the long-term spot size or turbulence-induced beam spot size is investigated. In particular, to distinguish beam wander among different beam types, the relative beam wander is defined. Based on this definition, the increment of beam wander between focused and collimated beam is larger than that of arbitrary beam type (i.e., $0<\Theta_0<1$). It is beneficial to select the predominant beam type in laser propagation applications

1. Introduction

Movement of the short-term beam instantaneous center (or "hot spot") is commonly called beam wander [1]. This phenomenon can be characterized statistically by the variance of the hot spot displacement along an axis or by the variance of the magnitude of the hot spot displacement [1]. An estimate of the short-term beam radius is obtained by removing beam wander effects from the long-term beam radius [1]. It is much convenient to use the geometrical optics approximation method in the turbulent area. Beam wander is an important characteristic of laser beams, which determines their utility for practical applications, such as laser communication [2,3], global quantum communication [4]. Until now, beam wander analysis in an optical ground station-satellite uplink has been reported [2]. Influence of beam wander on uplink of ground-to-satellite laser communication and optimization for transmitter beam radius has been researched [3]. Berman et al. have discussed the influence of the initial spatially coherent length on the beam wander [5]. The beam wander of various beam has been investigated, such as dark hollow beam, flat-topped beam, annular beam, cosh-Gaussian beam, Bessel beam, twin thin beam, electromagnetic Gaussian-Schell beam, Gaussian Schell-model beam, quantization Gaussian beam and Airy beam [6–13]. Compared to the optical propagation through the turbulent atmosphere, light propagation through seawater is relatively unexplored. Since the power spectrum of oceanic turbulence proposed by Nikishov and Nikishov [14], there has been remarkable interest in the study of propagation characteristics using laser beams in seawater. The power spectrum of oceanic turbulence has been simplified for homogeneous and isotropic water media in Ref. [15]. This spectrum is applicable for isothermal water and invalid for dominating salinity-induced optical turbulence (i.e., $w=0$) in detail [16]. Since recently the interest in active optical underwater communications, imaging and sensing appeared [17,18], it has become important to deeply understand how the oceanic turbulence affects laser propagation [19–22]. Recently, the effect of polarization characteristics [20], the intensity and coherence properties of light [21] and light scintillation [22] in oceanic turbulence have been studied, respectively. Very recently, the wave structure function and the radial Gaussian laser array beams propagating in oceanic turbulence have also been researched [16,23]. However, to the best of our knowledge, beam wander of laser beam propagating through oceanic turbulence has not been reported. In

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this paper, based on the oceanic power spectrum, we analyze the beam wander effect with analytical and numerical methods. It is believed that these results can be used in practical applications.

2. Beam wander of laser beam

The far-field angular spread of a free-space propagating beam of diameter $2W_0$ is of order $\lambda/2W_0$. In the presence of optical turbulence, a finite optical beam will experience random deflections as it propagates, causing further spreading of the beam by large-scale inhomogeneities of the turbulence [1]. Over short time periods the beam profile at the receiver moves off the boresight and can become highly skewed from Gaussian so that the instantaneous center of the beam is randomly displaced [1]. According to Ref. [1], W^2T_{LS} describes the beam wander or the variance of the instantaneous center of the beam in the receiver plane ($z = L$).

Based on the introduction of a general model [1], beam wander can be expressed as

$$a\left\langle r_c^2\right\rangle = W^2T_{LS} = 4\pi^2k^2W^2\int_0^L\int_0^\infty \kappa\Phi_n(\kappa)H_{LS}(\kappa,z)[1-\exp(-\Lambda L\kappa^2\xi^2/k)]\mathrm{d}\kappa\,\mathrm{d}z, \tag{1}$$

where <> denotes an ensemble average, k is the wave number related to the wavelength λ by $k=2\pi/\lambda$. W, Λ represents the beam radius in the free space and Fresnel ration of beam at receiver, respectively. $\Phi_n(\kappa)$ is the power spectrum of turbulence, $H_{LS}(\kappa, z)$ is the large-scale filter function, κ is the magnitude of spatial wave number, the normalized distance variable $\xi = 1 - z/L$.

According to Ref. [20], when the eddy thermal diffusivity and the diffusion of salt are assumed to be equal, the power spectrum for homogeneous and isotropic oceanic water is given by the expression

$$\Phi_n(\kappa) = 0.388\times10^{-8}\varepsilon^{-1/3}\chi_T\kappa^{-11/3}[1+2.35(\kappa\eta)^{2/3}] \times[w^2\exp(-A_T\delta)+\exp(-A_S\delta)-2w\exp(-A_{TS}\delta)]/w^2, \tag{2}$$

where ε is the rate of dissipation of kinetic energy per unit mass of fluid ranging from $10^{-1}\,\mathrm{m}^2/\mathrm{s}^3$ to $10^{-10}\,\mathrm{m}^2/\mathrm{s}^3$ [20], and χ_T is the rate of dissipation of mean-squared temperature ranging from $10^{-4}\,\mathrm{K}^2/\mathrm{s}$ to $10^{-10}\,\mathrm{K}^2/\mathrm{s}$ [20]. w (unitless) is the ratio of temperature to salinity contribution to the refractive index spectrum, which in oceanic waters varies in the interval [−5; 0], with −5 and 0 corresponding to dominating temperature-induced and salinity-induced optical turbulence, respectively [20]. $\eta = 10^{-3}$m is the Kolmogorov micro scale (inner scale). Besides, $A_T = 1.863\times10^{-2}$, $A_S = 1.9\times10^{-4}$, $A_{TS} = 9.41\times10^{-3}$ and $\delta = 8.284(\kappa\eta)^{4/3}+12.978(\kappa\eta)^2$.

The large-scale filter function is [1]

$$H_{LS}(\kappa,\xi) = \exp\{-\kappa^2W_0^2[(\Theta_0+\bar{\Theta}_0\xi)^2+\Lambda_0^2(1-\xi)^2]\}, \tag{3}$$

where $\Theta_0 = 1-\bar{\Theta}_0$. W_0, Θ_0 and Λ_0 are the beam radius, the beam curvature parameter and Fresnel ration of beam at transmitter, respectively [1].

Because beam wander is caused mostly by a large-scale turbulence near the transmitter, the last term can be dropped in (3) and the geometrical optics approximation is [1]

$$1-\exp(-\Lambda L\kappa^2\xi^2/k) = \Lambda L\kappa^2\xi^2/k,\quad L\kappa^2/k\ll1. \tag{4}$$

Substituting from Eqs. (2)–(4) into Eq. (1), Eq. (1) leads to

$$\left\langle r_c^2\right\rangle = 0.388\times10^{-8}\times4\pi^2kW^2L\Lambda\varepsilon^{-1/3}(\chi_T/w^2) \times\int_0^1\int_0^\infty\kappa^{-2/3}[1+2.35(\kappa\eta)^{2/3}] \times[w^2\exp(-A_T\delta)+\exp(-A_S\delta)-2w\exp(-A_{TS}\delta)] \times\exp[-\kappa^2W_0^2(\Theta_0+\bar{\Theta}_0\xi)^2]\xi^2\,\mathrm{d}\kappa\,d\xi, \tag{5}$$

then

$$\left\langle r_c^2\right\rangle = 0.388\times10^{-8}\times4\pi^2kW^2L\Lambda\varepsilon^{-1/3}(\chi_T/w^2)\int_0^1\xi^2\,d\xi \times\int_0^\infty(\kappa^{-2/3}+g)[w^2\exp(-a\kappa^{4/3}-b\kappa^2) +\exp(-c\kappa^{4/3}-d\kappa^2)-2w\exp(-e\kappa^{4/3}-f\kappa^2)]\,\mathrm{d}\kappa, \tag{6}$$

where $a = 8.284A_T\eta^{4/3}$, $b = 12.978A_T\eta^2+W_0^2\left(\Theta_0+\bar{\Theta}_0\xi\right)^2$, $c = 8.284A_S\eta^{4/3}$, $d = 12.978A_S\eta^2+W_0^2\left(\Theta_0+\bar{\Theta}_0\xi\right)^2$, $e = 8.284A_{TS}\eta^{4/3}$, $f = 12.978A_{TS}\eta^2+W_0^2\left(\Theta_0+\bar{\Theta}_0\xi\right)^2$, $g = 2.35\eta^{2/3}$.

After very tedious calculations, the beam wander is expressed as

$$\begin{aligned}\left\langle r_c^2\right\rangle = {}&0.388\times10^{-8}\times4\pi^2kW^2L\Lambda\varepsilon^{-1/3}(\chi_T/w^2)\\ &\times\int_0^1\xi^2\left\{w^2b^{-1/6}\Gamma(1/6)(1-7a^3/216b^2)/2\right.\\ &+d^{-1/6}\Gamma(1/6)(1-7c^3/216d^2)/2\\ &-wf^{-1/6}\Gamma(1/6)(1-7e^3/216f^2)\\ &-w^2ab^{-5/6}\Gamma(5/6)(1-55a^3/864b^2)/2\\ &-cd^{-5/6}\Gamma(5/6)(1-55c^3/864d^2)/2\\ &+wef^{-5/6}\Gamma(5/6)(1-55e^3/864f^2)\\ &+w^2a^2b^{-3/2}\Gamma(3/2)(1-a^3/16b^2)/4\\ &+c^2d^{-3/2}\Gamma(3/2)(1-c^3/16d^2)/4\\ &-we^2f^{-3/2}\Gamma(3/2)(1-e^3/16f^2)/2\\ &+w^2gb^{-1/2}\Gamma(1/2)(1-a^3/8b^2)/2\\ &+gd^{-1/2}\Gamma(1/2)(1-c^3/8d^2)/2\\ &-wgf^{-1/2}\Gamma(1/2)(1-e^3/8f^2)\\ &-w^2gab^{-7/6}\Gamma(7/6)(1-91a^3/864b^2)/2\\ &-gcd^{-7/6}\Gamma(7/6)(1-91c^3/864d^2)/2\\ &+wgef^{-7/6}\Gamma(7/6)(1-91e^3/864f^2)\\ &+w^2ga^2b^{-11/6}\Gamma(11/6)(1-187a^3/2160b^2)/4\\ &+gc^2d^{-11/6}\Gamma(11/6)(1-187c^3/2160d^2)/4\\ &\left.-wge^2f^{-11/6}\Gamma(11/6)(1-187a^3/2160b^2)/2\right\}d\xi.\end{aligned} \tag{7}$$

where $\Gamma(\bullet)$ is the Gamma function and Eq. (7) is applicable for collimated, divergent or focused Gaussian beam. In our paper, we analyze two special cases (i.e., collimated beam and focused beam).

For collimated beam $\left(\Theta_0 = 1\right)$, Eq. (7) can be simplified as

$$\left\langle r_c^2\right\rangle_{coll} = 0.517\times10^{-8}\times\pi^2kW^2L\Lambda\varepsilon^{-1/3}(\chi_T/w^2) \times(\alpha w^2-2\beta w+\gamma), \tag{8}$$