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Aperture averaging in strong oceanic turbulence

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A B S T R A C T

Receiver aperture averaging technique is employed in underwater wireless optical communication (UWOC) systems to mitigate the effects of oceanic turbulence, thus to improve the system performance. The irradiance flux variance is a measure of the intensity fluctuations on a lens of the receiver aperture. Using the modified Rytov theory which uses the small-scale and large-scale spatial filters, and our previously presented expression that shows the atmospheric structure constant in terms of oceanic turbulence parameters, we evaluate the irradiance flux variance and the aperture averaging factor of a spherical wave in strong oceanic turbulence. Irradiance flux variance variations are examined versus the oceanic turbulence parameters and the receiver aperture diameter are examined in strong oceanic turbulence. Also, the effect of the receiver aperture diameter on the aperture averaging factor is presented in strong oceanic turbulence.

1. Introduction

UWOC systems have gained great interest in recent years because the ability to use of blue–green bands of the spectrum have launched investigations on military, environmental and sensor network applications in underwater [1–3]. The major challenge for the UWOC systems is the oceanic turbulence which originates from the salinity, temperature and density fluctuations. The oceanic turbulence affects the laser beam propagation in many ways such as the beam wander, beam spreading, fluctuations in the amplitude, phase, and intensity fluctuations (also known as scintillation) which cause the optical communication performance to decrease [4].

Oceanic and atmospheric turbulence share similar concepts. There were significant research efforts on atmospheric turbulence. For instance, the scintillation of an optical wave propagating through atmosphere has been well documented with the help of Rytov theory and extended Huygens–Fresnel principle [4–8]. These investigations of the atmospheric turbulence have led to analyze and understand also the nature of the oceanic turbulence. This way, researchers have studied and modeled the oceanic turbulence in order to evaluate the scintillations and other optical entities such as the average intensity, probability density function, spatial coherence radius of a wave, and the structure functions in underwater [9–14]. Moreover, the scintillations of spherical, plane and the Gaussian beam waves in weak and strong oceanic turbulence have been reported [15–19].

Scintillation, namely turbulence induced signal fading reduces the UWOC system performance. There are several techniques that help the UWOC system performance to improve. For instance, spatial diversity systems which use multiple transmitters and receivers are one of the solutions for scintillation reduction [20–22]. Another scintillation reduction technique is the use of different beam types at the transmitter [23,24]. Here, we analyze the aperture averaging technique which is achieved by enlarging the receiver aperture area as a means of reducing the scintillation. In this way, relatively high spatial frequency content of the intensity fluctuations on the aperture shifts toward the lower frequencies. Intensity fluctuations on a hard aperture can be measured by the irradiance flux variance. In the literature, irradiance flux variance for the spherical wave propagating through weak oceanic turbulence has been studied [25]. However, to our knowledge, aperture averaged scintillation of the spherical wave under strong oceanic turbulence condition has not been reported yet. Therefore, using the modified Rytov theory [5–7] and the equivalent structure constant of the atmosphere [9], the irradiance flux variance and the aperture averaging factor for a spherical wave which propagate horizontally through strong oceanic turbulence is scrutinized.

2. Formulation

The conventional Rytov theory is valid in weak turbulence in describing the irradiance fluctuations. However, the modified Rytov theory uses

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small-scale and large scale spatial filters to find the scintillation index in weak-to-strong atmospheric turbulence [5–7]. In a similar manner, the irradiance flux variance of a spherical wave on a lens of hard aperture diameter D can be expressed as follows [5–7]

$$\sigma_I^2(D) = \exp\left[\sigma_{\ln x}^2(D) + \sigma_{\ln y}^2(D)\right] - 1 \simeq \exp\left[\frac{0.49\beta_0^2}{\left(1+0.18d^2+0.56\beta_0^{12/5}\right)^{7/6}} + \frac{0.51\beta_0^2\left(1+0.69\beta_0^{12/5}\right)^{-5/6}}{1+0.90d^2+0.62d^2\beta_0^{12/5}}\right] - 1, \tag{1}$$

where $\sigma_{\ln x}^2(D)$ and $\sigma_{\ln y}^2(D)$ are the large-scale and the small-scale log-irradiance flux variances, respectively. $\beta_0^2 = 0.5C_n^2 k^{7/6} L^{11/6}$ is the conventional Rytov variance for a spherical wave, $d = \left(0.25kD^2/L\right)^{0.5}$, L is the link length, and $k = 2\pi\lambda^{-1}$, λ being the wavelength. Note that the case for $D = 0$ in Eq. (1) shows the point detector scintillation of a spherical wave. Our aim is to find the irradiance flux variance in strong oceanic turbulence. Thus, we use our earlier result [9] that expresses the structure constant of atmospheric turbulence in β_0^2 by means of oceanic turbulence parameters, namely the rate of dissipation of mean-squared temperature, the rate of dissipation of kinetic energy per unit mass of fluid, the ratio of temperature to salinity contributions to the refractive index spectrum and kinematic viscosity [9]. That is

$$C_n^2 = 16\pi^2 k^{-7/6} L^{-11/6} \mathrm{Re}\left\{\int_0^L d\varsigma \int_0^\infty \kappa d\kappa \left[E(\varsigma,\kappa,L)\times E(\varsigma,-\kappa,L) + |E(\varsigma,\kappa,L)|^2\right]\Phi(\kappa)\right\}, \tag{2}$$

where for the spherical wave,

$$E(\varsigma,\kappa,L) = ik\exp\left[-\frac{0.5i\varsigma(L-\varsigma)\kappa^2}{kL}\right], \tag{3}$$

where $i = \sqrt{-1}$, κ is the magnitude of the spatial frequency and $\Phi(\kappa)$ is the power spectrum of oceanic fluctuations. In isotropic and homogeneous turbulence (i.e., thermal diffusivity and diffusion of salt are equal to each other) $\Phi(\kappa)$ takes the form [14]

$$\Phi_n(\kappa) = 0.388\times10^{-8}\varepsilon^{-1/3}\kappa^{-11/3}\left(1+2.35\kappa^{2/3}\upsilon^{1/2}\varepsilon^{-1/6}\right) \times \frac{X_T}{\omega^2}\left(\omega^2 e^{-A_T\delta} + e^{-A_S\delta} - 2\omega e^{-A_{TS}\delta}\right), \tag{4}$$

where X_T is the rate of dissipation of mean-squared temperature. Values of X_T typically range from 10^{-10} K^2/s for the deep water and up to 10^{-4} K^2/s or more for the surface water. ε is the rate of dissipation of kinetic energy per unit mass of fluid which may take values in the interval 10^{-8} to 10^{-2} m^2/s^3 (i.e., deep water to surface water) [1,2], $\omega = [-5, 0]$ is the unitless parameter providing the ratio of temperature to salinity contributions to the refractive index spectrum. If ω becomes smaller, oceanic turbulence is dominated by the temperature fluctuations that we call the temperature-driven turbulence and if ω becomes larger, turbulence is dominated by salinity fluctuations, thus salinity-driven turbulence is obtained. υ is the kinematic viscosity in m^2/s and expressed as $\upsilon = \eta^{4/3}\varepsilon^{1/3}$ where η is the Kolmogorov microscale length. $\delta(\kappa,\eta) = 8.284\kappa^{4/3}\upsilon\varepsilon^{-1/3} + 12.978\kappa^2\upsilon^{3/2}\varepsilon^{-1/2}$, $A_S = 1.9\times10^{-4}$, $A_T = 1.863\times10^{-2}$, and $A_{TS} = 9.41\times10^{-3}$.

Aperture averaging factor is defined as ratio of the irradiance flux variance obtained by a finite sized aperture to a scintillation obtained by a point detector. That is

$$A = \frac{\sigma_I^2(D)}{\sigma_I^2(D=0)}. \tag{5}$$

A typically takes values between 0 and 1 because the irradiance flux variance obtained by a finite sized aperture is generally smaller than the scintillation obtained by a point detector. Therefore, A should be close to zero for effective aperture averaging.

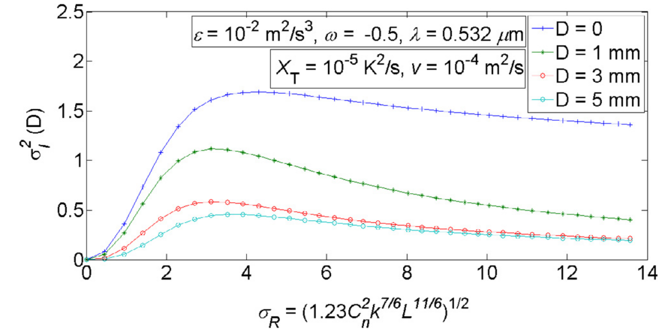

Fig. 1. Irradiance flux variance of a spherical wave versus σ_R for various aperture diameters.

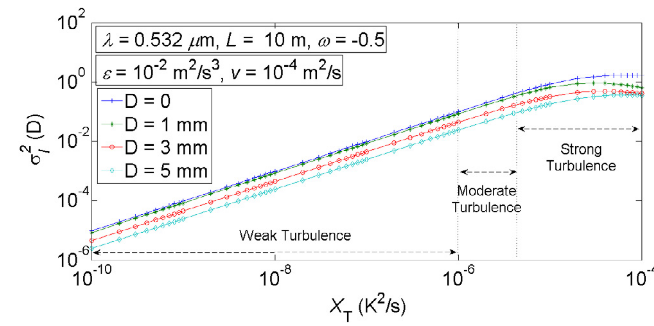

Fig. 2. Irradiance flux variance of a spherical wave versus broad range of the rate of dissipation of the mean-squared temperature X_T (to cover all turbulence regimes) for various aperture diameters.

3. Results and discussions

In this section, in order to classify the strength of turbulence, Rytov variance for the plane wave $\sigma_R^2 = 1.23C_n^2 k^{7/6} L^{11/6}$ is used [5] where for C_n^2 the corresponding value in terms of the oceanic turbulence parameters obtained from the expression given in Eq. (2) is employed. For instance, weak turbulence is characterized by $\sigma_R^2 < 0.3$, moderate turbulence is associated with $0.3 < \sigma_R^2 < 1$, whereas strong turbulence is represented by $\sigma_R^2 > 1$. In the figures provided, regions of the turbulence are also shown based on σ_R^2. In Fig. 1, we aimed at demonstrating the irradiance flux variance of spherical wave versus σ_R. Note that the case of $D = 0$ in Fig. 1 shows the scintillation index of a point detector which closely reduces to the scintillation index in Fig. 2 of Ref. [7]. Therefore, $D = 0$ in Fig. 1 is the check case of our formulation. We let the link distance increase but assume $\varepsilon = 10^{-2}$ m^2/s^3, $\omega = -0.5$, $X_T = 10^{-5}$ K^2/s, $\upsilon = 10^{-4}$ m^2/s. As seen from Fig. 1, little increment in the receiver aperture size causes notable reduction on the irradiance flux variance. The behavior depicted in Fig. 1 agrees with the known results for strong atmospheric turbulence [5–7].

In Figs. 2 and 3, the irradiance flux variance is analyzed as a function of the rate of dissipation of the mean-squared temperature X_T for various collecting lens of diameters. Note that Fig. 3 covers Fig. 2 but Fig. 3 is restricted to conditions of moderate and strong irradiance fluctuations ($0.3 < \sigma_R^2 < 1$, $\sigma_R^2 > 1$, respectively). It is seen in Fig. 2 that as X_T increases in a logarithmic scale, the irradiance flux variance initially increases, then saturates to different levels depending on D. In order to scrutinize the irradiance fluctuations in the moderate and strong oceanic turbulence regimes, Fig. 3 is sketched where lowest irradiance flux variance is obtained for the largest receiver aperture diameter $D = 5$ mm.

The variations of the irradiance flux variance as a function of rate of dissipation of kinetic energy per unit mass of fluid ε are provided in Fig. 4 for various D values where it is sketched for the same parameters