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Cross-beam scintillations in underwater medium

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Abstract. The fluctuation in the intensity, which is quantified by the scintillation index, is evaluated for cross beams when such beams propagate in an underwater medium experiencing turbulence. The variations in the scintillation index are investigated against the changes in the size of the cross beams, the ratio of temperature to salinity contributions to the refractive index spectrum, the rate of dissipation of mean-squared temperature, and the rate of dissipation of kinetic energy per unit mass of fluid. [DOI: 10.1117/1.OE.55.11.111612]

Keywords: underwater turbulence; scintillation; cross beam.

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1 Introduction

Intensity fluctuations in turbulence are affected by many factors, such as the wavelength of operation, link length, the magnitude of the variations of the refractive index, link configuration, the sizes and the number of the optical detectors, and the optical field profiles of the light sources employed. Numerous results are reported in this area for the last several decades. In this paper, since we focus ourselves on the effect of cross beams on the scintillation index, as the references, we will mention only the beam effects on the scintillations. In this respect, the effects of various beam types on the scintillation index are investigated in atmospheric turbulence, some of which can be found in Refs. 1–10. Some of these results are summarized in the review paper.[11] Regarding the cross beams, which is the subject of this paper, we have lately reported their propagation aspects[12] and the scintillations in Kolmogorov[13] and non-Kolmogorov[14] atmospheric turbulence.

On the other hand, optical wireless communication is becoming quite popular in underwater/oceanic medium.[15–17] Water degrades the light properties due to the presence of various constituents in water. These result in scattering and absorption in the optical received signal, thus causing extra loss of optical power. Additionally, the random variations in the refractive index of water, mainly because of the fluctuations in the salinity and temperature, cause the received intensity to fluctuate, which degrades the performance of optical wireless communication links operating in underwater/oceanic medium. Turbulent behavior of water and its effects on signals can be found in detail in literature.[18,19] In a similar manner as in the atmosphere, the effects of various beam types on the scintillation index are also scrutinized in underwater/oceanic turbulence.[20–24]

In this paper, we have evaluated the scintillation index at the receiver plane of cross beams propagating in underwater/oceanic turbulence. Our motivation is to understand whether the use of different beam types, such as the cross beam as in this paper, will help to improve the optical wireless communication link performance operating in an underwater/oceanic environment.

2 Formulation

In this paper, the results are obtained based on our theoretical analysis. We intend to do the corresponding experiments in our future work. In Fig. 1, the configuration used in our theoretical analysis is shown. In fact, the experimental setup will be the same except that the cross beam, turbulent medium, and the point detector will be replaced by spatial light modulator (SLM) generating the cross beam with plano–convex lens in front of the SLM, water tank in which turbulence will be generated and small aperture avalanche photo diode operating at 0.532 μm, respectively.

In collimated cross beams, the optical field at the source plane is given by[13]

$$u_s = \sum_{j=1}^{2} A_j \exp[-0.5(\alpha_{sxj}^{-2} s_x^2 + \alpha_{syj}^{-2} s_y^2)], \tag{1}$$

where (s_x, s_y) are the transverse x and y coordinates at the source plane, A_j is the amplitude of the j'th Gaussian beam, $j = 1,2$, α_{sxj} and α_{syj} are the source sizes in the x- and y-directions. From Eq. (1), it is seen that the cross beam is composed of two asymmetrical Gaussian beams that are perpendicular to each other. One of the two asymmetrical Gaussian beams is wider along the x-axis and the other Gaussian beam is wider along the y-axis.

By the use of Rytov method, we have previously formulated[25] for the general type beams, the log-amplitude correlation function $B_\chi(L)$ in turbulence at the link length of L, which is used to find the scintillation index m^2 of cross beams at the receiver plane after the cross beam propagates in weak atmospheric turbulence.[13,14] In weak turbulence, it is known[26] that the scintillation index can be reasonably approximated by $4B_\chi(L)$. The formula for the scintillation index of cross beam in weak atmospheric turbulence provided in Refs. 13 and 14 is expressed below, this time for the underwater/oceanic weak turbulence. We note that the structure of the scintillation index formula for the underwater/oceanic weak turbulence is the same as the formula for the atmospheric weak turbulence[13,14] except that the spectral density of the index of refraction fluctuations valid for

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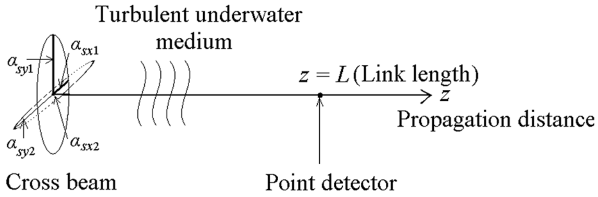

Fig. 1 Configuration of the turbulent underwater link.

the underwater/oceanic turbulence replaces the spectral density of the index of refraction fluctuations valid for the atmospheric turbulence. Thus, the scintillation index at the receiver plane of the cross beams in weak underwater/oceanic turbulence is given as[13,14]

$$m^2 = 4B_\chi(L) = 4\pi \mathrm{Re}\left\{\int_0^L \mathrm{d}z \int_0^\infty \kappa d\kappa \int_0^{2\pi} \mathrm{d}\theta [M_1(z,\kappa,\theta) + M_2(z,\kappa,\theta)]\Phi_n(\kappa)\right\}, \tag{2}$$

where Re denotes the real part, z is the parameter indicating the distance, $\boldsymbol{\kappa} = \kappa e^{i\theta}$ is the spatial frequency vector, $\kappa = |\boldsymbol{\kappa}| = (\kappa_x^2 + \kappa_y^2)^{1/2}$ and θ are the amplitude and the phase of the spatial frequency, with $\kappa_x = \kappa \cos\theta$, $\kappa_y = \kappa \sin\theta$, $d^2\boldsymbol{\kappa} = d\kappa_x d\kappa_y = \kappa d\kappa d\theta$, and $\Phi_n(\kappa)$ is the spectral density of the index of refraction fluctuations in underwater/oceanic turbulence, which is given by[27]

$$\Phi_n(\kappa) = 0.388 \times 10^{-8} \varepsilon^{-1/3} \kappa^{-11/3} [1 + 2.35(\kappa\eta)^{2/3}] \times \frac{X_T}{w^2}(w^2 e^{-A_T\delta} + e^{-A_S\delta} - 2we^{-A_{TS}\delta}), \tag{3}$$

where X_T is the rate of dissipation of mean-squared temperature, ε is the rate of dissipation of kinetic energy per unit mass of fluid, η is the Kolmogorov microscale, known as the inner scale, w is a unitless parameter, which is the ratio of temperature to salinity contributions to the refractive index spectrum. $w = -5$ defines temperature-dominated underwater turbulence, whereas $w = 0$ defines salinity-dominated underwater turbulence. Here, $A_S = 1.9 \times 10^{-4}$, $A_T = 1.863 \times 10^{-2}$, $A_{TS} = 9.41 \times 10^{-3}$, and $\delta(\kappa,\eta) = 8.284(\kappa\eta)^{4/3} + 12.978(\kappa\eta)^2$. The other entities in Eq. (2) are defined as $M_1(z,\kappa,\theta) = N(z,\kappa,\theta) N(z,-\kappa,\theta)/[D(L)D(L)]$, $M_2(z,\kappa,\theta) = N(z,\kappa,\theta)N^*(z,\kappa,\theta)/[D(L)D^*(L)]$, $D(L) = \sum_{j=1}^2 A_j[(1 + i\frac{L}{k\alpha_{sxj}^2})(1 + i\frac{L}{k\alpha_{syj}^2})]^{-1/2}$,

$$N(\eta,\kappa,\theta) = ik\sum_{j=1}^2 A_j \frac{\exp\left\{\frac{0.5i}{k}(z-L)\kappa^2\left[\frac{\left(1 + i\frac{z}{k\alpha_{sxj}^2}\right)}{\left(1 + i\frac{L}{k\alpha_{sxj}^2}\right)}\cos^2\theta + \frac{\left(1 + i\frac{z}{k\alpha_{syj}^2}\right)}{\left(1 + i\frac{L}{k\alpha_{syj}^2}\right)}\sin^2\theta\right]\right\}}{\sqrt{\left(1 + i\frac{L}{k\alpha_{sxj}^2}\right)\left(1 + i\frac{L}{k\alpha_{syj}^2}\right)}}, \quad k = 2\pi/\lambda$$

λ is the wavelength, and $i = (-1)^{0.5}$.

We note that the scintillation index in general depends on the bandwidth of the optical beam employed in the wireless optical communication link operating in underwater medium. As shown for atmospheric turbulence, this dependence is in the form of reduction of the scintillations as the bandwidth inceases.[28,29] However, this reduction is negligibly small in weak atmospheric turbulence.[28,29] This is because the bandwidth, even at very high data rate transmission, is very much smaller than the optical carrier frequency, which means that the communications optical signal practically acts like a monochromatic beam in weak turbulence. Bandwidth becomes effective only in very strong turbulence.[29] Our analysis in this paper is for a monochromatic beam in weakly turbulent underwater medium, i.e., no bandwidth of optical communication link in underwater is considered. Bandwidth effects on the scintillations are not examined in underwater turbulence and will be the topic of our future work. Making use of the results from Refs. 28 and 29, taking into account that the bandwidth is very much smaller than the optical carrier frequency and weak underwater turbulence is examined, our results presented in this paper practically will not be effected by the bandwidth.

3 Results and Discussions

In the figures provided in this section, $\mathrm{AF}_1 = \alpha_{sy1}/\alpha_{sx1}$ and $\mathrm{AF}_2 = \alpha_{sy2}/\alpha_{sx2}$ are defined as the asymmetry factors of the first and the second asymmetrical Gaussian beam that compose the cross beam. Figures 2–4 are plotted at fixed underwater turbulence parameters to show the variations of the scintillation index of cross beams versus $\alpha_{sx1}/(\lambda L)^{1/2}$, i.e., the source size in the x-direction of the first Gaussian beam that forms the cross beam, normalized by the Fresnel zone. In Figs. 5–7, the scintillation indices are plotted versus the ratio of temperature to salinity contributions to the refractive index spectrum w, the rate of dissipation of mean-squared temperature X_T, and the rate of dissipation of kinetic energy per unit mass of fluid ε, respectively. In Figs. 5–7, for simplicity, the source size in the x-direction

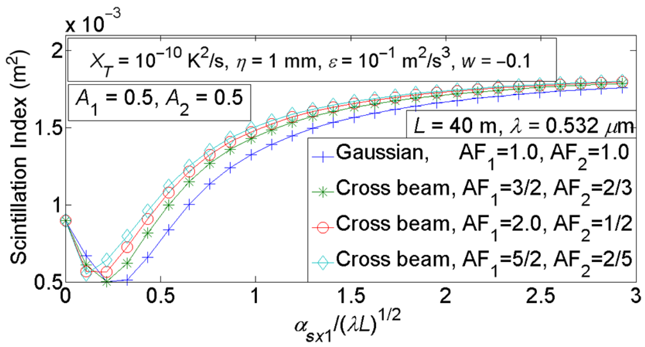

Fig. 2 Scintillation index in underwater turbulence versus the normalized source size of cross beams with individual beams having asymmetry factors, which are inverse of each other.

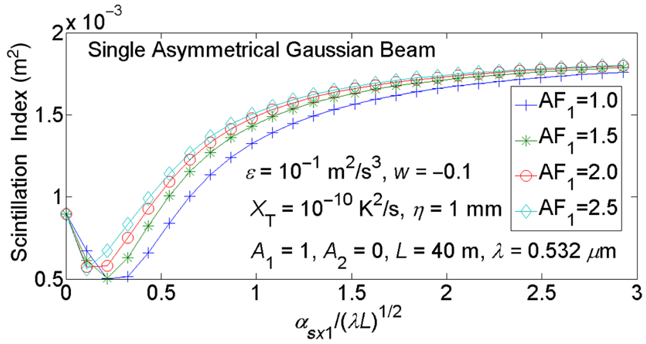

Fig. 3 Scintillation index versus the normalized source size of asymmetrical Gaussian beams in underwater turbulence.

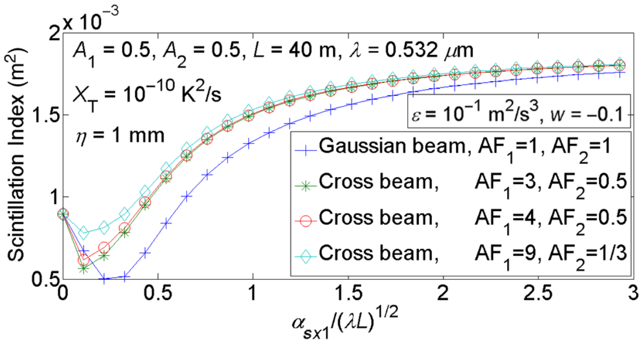

Fig. 4 Scintillation index in underwater turbulence versus the normalized source size of cross beams with individual beams having independent asymmetry factors.

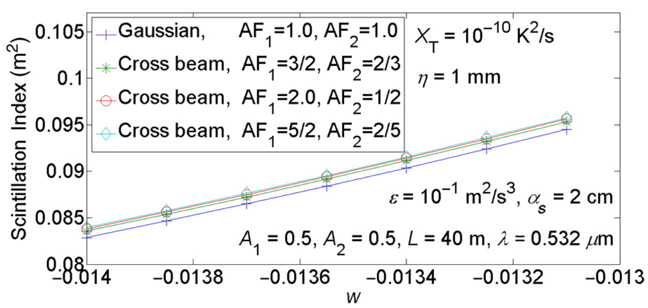

Fig. 5 Scintillation index in underwater turbulence versus w of cross beams with individual beams having asymmetry factors, which are inverse of each other.

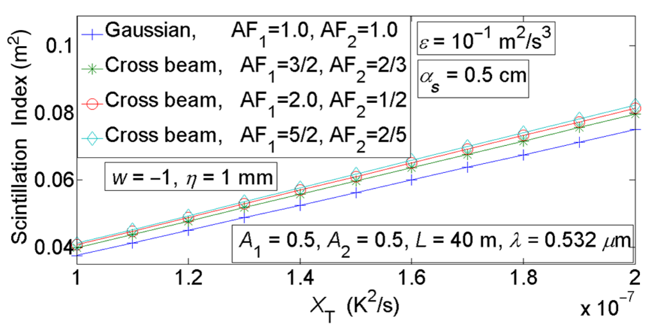

Fig. 6 Scintillation index in underwater turbulence versus X_T of cross beams with individual beams having asymmetry factors, which are inverse of each other.

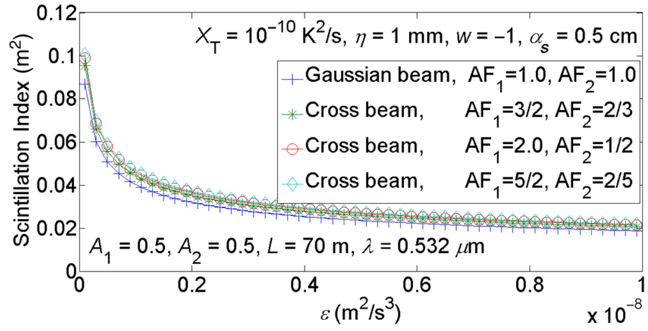

Fig. 7 Scintillation index in underwater turbulence versus ε of cross beams with individual beams having asymmetry factors, which are inverse of each other.

of the first Gaussian beam is shown by α_s, i.e., $\alpha_s = \alpha_{sx1}$. Also, in all the figures, except in Fig. 3, the amplitudes of both beams composing the cross beams are taken to be $A_1 = A_2 = 0.5$ whereas in Figs. 3, since single asymmetrical beams are examined, the amplitude of the single asymmetrical beam is taken as $A = 1$, and since there is no second beam the amplitude of the second beam is zero. In all the figures, other relevant underwater turbulence parameters are shown in the legends of these figures.

In Fig. 2, the cross beams are structured such that the single beams composing the cross beam have asymmetry factors that are inverse of each other, i.e., $\mathrm{AF}_1 = 1/\mathrm{AF}_2$. Naturally, taking $\mathrm{AF}_1 = \mathrm{AF}_2 = 1$, cross beam field becomes the Gaussian beam. Figure 2 shows that, at the chosen underwater turbulence parameters, increasing the source size, first decreases the scintillations, after reaching a minimum, the scintillations start to increase and eventually the scintillations stay at a fixed value for large size sources, i.e., when the source approaches a plane wave. It is also observed from Fig. 2 that at a fixed relatively large source size, the cross beams attain larger scintillation values as compared to the Gaussian beam, the ones with larger asymmetry factors having larger intensity fluctuations. This can be attributed to the fact that cross beams having two asymmetrical Gaussian beams will have larger beam wander as compared to single Gaussian beam. This explanation is supported by the findings in Ref. 30 where root mean square beam wander is evaluated in atmospheric turbulence and for most source sizes, the quantitative values of the beam wander of asymmetrical Gaussian beam are found to be larger than the beam wander of symmetrical Gaussian beam.[30] Being one of the factors influencing the intensity fluctuations, larger beam wander will cause the cross beams to have larger scintillations. In Fig. 3, single asymmetrical beam scintillations are examined in underwater turbulence. We note that the underwater medium characteristics in Fig. 3 are chosen the same as in Fig. 2. It is observed that the scintillation behavior of the single asymmetrical beams is the same as the scintillation behavior of the cross beams. At sufficiently large source sizes, more asymmetrical beams seem to have larger intensity fluctuations in underwater medium. With the same medium parameters, Fig. 2 is replotted in Fig. 4 by using cross beams with asymmetry factors of each individual beam independent of each other. Again, the trend of the scintillations of cross beams with asymmetry factors of each individual beam independent of each other that are provided in Fig. 4 are similar to the trend of the scintillations of cross beams with asymmetry factors that are inverse of each other, which are provided in Fig. 2. The cross beams with larger asymmetry factors exhibit larger scintillations in underwater turbulence. Physical interpretation of this result is again related to the fact that the scintillation index increases with the increase in the beam wander, and the cross beams having larger asymmetry factors will have larger beam wander as compared to the cross beams having smaller asymmetry factors. From Fig. 5, we arrive at the conclusion that larger ratio of temperature to salinity contributions to the refractive index spectrum w causes the intensity of the cross beams to fluctuate more, and at the same w, cross beams having larger asymmetry factors scintillate more. However, the difference in the scintillation index values of cross beams possessing different asymmetry factors is not substantial. Figure 6 indicates that the effect of the rate of dissipation of mean-squared temperature X_T on the scintillations is similar to the effect of the ratio of temperature to salinity contributions to the refractive index spectrum, w provided in Fig. 5, i.e., larger rate of dissipation of mean-squared temperature X_T causes the intensity of the cross beams to fluctuate more, and at the same X_T, cross beams having larger asymmetry factors scintillate more. From Fig. 7, it is understood that as the rate of dissipation of kinetic energy per unit mass of fluid, ε increases, the scintillation index becomes smaller for all the cross beams, and this decrease is much sharper at smaller ε. At sufficiently large values of the rate of dissipation of kinetic energy per unit mass of fluid, for all the cross beams, the scintillations tend to stay at a steady value in underwater turbulence. Another observation from Fig. 7 is that when the rate of dissipation of kinetic energy per unit mass of fluid ε is kept fixed, the cross beams with larger asymmetry factors have larger intensity fluctuations.

One of the findings in this paper is that when the ratio of the temperature to salinity contributions to the refractive index spectrum "w" increases, the scintillations of cross beams tend to increase, which is consistent with the results presented in Figs. 2–4 and 6 and 7. In Figs. 2–4, $w = -0.1$ and the scintillation index is in the range from 5×10^{-4} to 2×10^{-3}. In Figs. 6 and 7, $w = -1$ and the scintillation index is in the range from 2×10^{-2} to 1.2×10^{-1}. In Fig. 5, w is in the range from -0.014 to -0.013 and the scintillation index value varies from 8.2×10^{-2} to 9.6×10^{-2}. At the first glance it can be thought that in Fig. 5, the scintillation index has about the same value as that in Figs. 6 and 7, which corresponds to $w = -1$. This could be thought to be inconsistent with the claimed trend that when the ratio of the temperature to salinity contributions to the refractive index spectrum increases, the scintillations of cross beams tend to increase. However, this thought is misleading because a fare comparison of the scintillation index values in Fig. 5 with the scintillation index values in Figs. 6 and 7 can only be done under the same link and turbulence parameters. This is not the case in the comparison between the scintillation values in Figs. 5 and in Figs. 6 and 7. In Fig. 5, the source size is $\alpha_s = 2$ cm, whereas in Figs. 6 and 7, the source size is $\alpha_s = 0.5$ cm. Additionally, in Fig. 5, underwater parameters are $X_T = 10^{-10}\ \mathrm{K}^2/\mathrm{s}$ and $\varepsilon = 10^{-1}\ \mathrm{m}^2/\mathrm{s}^3$, where the horizontal axis value of X_T in Fig. 6 is far above $10^{-10}\ \mathrm{K}^2/\mathrm{s}$ and the horizontal axis value of ε in Fig. 7 is far below $10^{-1}\ \mathrm{m}^2/\mathrm{s}^3$, therefore a fare comparison of scintillation values of Fig. 5 and Figs. 6 and 7 cannot be made. Under a fare comparison, the finding in this paper, which states that when the ratio of the temperature to salinity contributions to the refractive index spectrum "w" increases, the scintillations of cross beams tend to increase, will always hold to be true.

4 Conclusion

The scintillation index of cross beams is evaluated after these beams propagate in a weakly underwater turbulent medium. It is found that as the source size of the cross beam (for sufficiently large sized cross beams), the ratio of temperature to salinity contributions to the refractive index spectrum w and the rate of dissipation of mean-squared temperature X_T increase, the scintillations of cross beams in underwater medium tend to increase. However, increase in the rate of dissipation of kinetic energy per unit mass of fluid ε decreases the scintillations of cross beams in underwater medium. Keeping all the source and turbulence parameters fixed, cross beams possessing higher asymmetry factors have larger intensity fluctuations.

Our results in this paper can be helpful in determining the performance characteristics of optical wireless communication systems operating in an underwater/oceanic medium when cross beams are employed in the link design.

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