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Experimental study: Underwater propagation of polarized flat top partially coherent laser beams with a varying degree of spatial coherence

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ABSTRACT

We report on experiments where spatially partially coherent laser beams with flat top intensity profiles were propagated underwater. Two scenarios were explored: still water and mechanically moved entrained salt scatterers. Gaussian, fully spatially coherent beams, and Multi-Gaussian Schell model beams with varying degrees of spatial coherence were used in the experiments. The main objective of our study was the exploration of the scintillation performance of scalar beams, with both vertical and horizontal polarizations, and the comparison with electromagnetic beams that have a randomly varying polarization. The results from our investigation show up to a 50% scintillation index reduction for the case with electromagnetic beams. In addition, we observed that the fully coherent beam performance deteriorates significantly relative to the spatially partially coherent beams when the conditions become more complex, changing from still water conditions to the propagation through mechanically moved entrained salt scatterers.

1. Introduction

Propagation of laser light through random media [1,2] is of great interest in developing a more complete understanding of the properties of laser light intensity fluctuations in all practical laser applications. Much of the recent research focus has been on laser propagation through turbulent atmospheric conditions, with an emphasis on laser light scintillation mitigation by source partial coherence [3–5], aperture averaging [6], sparse aperture detectors [7,8], wavelength diversity [9], source temporal variations [10], and polarization diversity [11–13]. The study of laser light propagation underwater is of significant importance for communication and sensing applications, in particular with submersible robots [14–17], but there are significant challenges in light intensity distortion mitigation that require detailed studies. Some of the challenging aspects of the underwater environment for laser propagation include interactions with the sea surface, multipath propagation, intensity fluctuations due to the index of refraction changes caused by temperature variation along the propagation path, and the scattering of light off particulates in the water. Background research on light scintillation in the ocean has been theoretically studied for plane, spherical, and Gaussian beams [18], and for partially coherent beams [19]. To the best of our knowledge, mitigation techniques using polarization diversity have not been experimentally explored in detail for the underwater environment. Our motivation to experiment with propagation of laser light underwater stems from our interest in applying to an underwater medium, source partial coherence variations and polarization diversity techniques that have been successfully implemented in reducing the scintillation of the laser light in a turbulent atmosphere [20–22]. These techniques are based on a statistical treatment of a complex propagating medium, and as such show the potential to improve the properties of laser light propagating in a complex underwater environment.

Multi-Gaussian Schell Model (MGSM) spatially partially coherent beams (PCB) [23] with a varying degree of spatial coherence have a flat top intensity profile, and can be created by a straightforward technique utilizing a spatial light modulator (SLM) which allows an effective spatial degree of coherence manipulation. Experimentally, the coherent laser beam is redistributed into independent beamlets by interacting with phase screens on the spatially distributed liquid crystal cells of the SLM. True PCBs theoretically require statistical realizations on an SLM changing at an infinite rate [24], which is not currently realizable with available instrumentation. Therefore, for our experiments we generate pseudo partially coherent beams (PPCBs) which describe a beam made using a finite cycling rate of SLM phase screens. Statistically, the propagation of spatially distributed beamlets with a random phase through complex medium results in a more even laser light intensity

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distribution on the target. This method constructs uniformly polarized scalar laser beams with varied source partial coherence.

Electromagnetic spatially partially coherent laser beams are constructed from the combination of horizontally and vertically polarized scalar beams [12,25,26]. It has been theoretically and experimentally [20,21,27] shown, in optical atmospheric turbulence, that electromagnetic spatially PCBs have a reduced scintillation index of up to 50% as compared to the scalar beams, but to our knowledge, this property has not been explored in an underwater environment. The basis for such a high reduction in laser light intensity fluctuations is related to the property that adding vertically and horizontally PCBs results in an arbitrary polarization of electromagnetic beam. The scalar beams in this experiment have a well-defined single angle polarization (vertical or horizontal) and their scintillation is related to both the induced variations from the cycling of the screens that produce the partial spatial coherence and the interaction of the laser beam with the water and moving entrained scatterers along the path of propagation. The constructed electromagnetic beams have the same spatial coherence as the scalar beams, propagate through the same environment, but also have a random phase. This randomization of the polarization effectively increases the chances of spatially distributed beamlets, to on average have reduced constructive and destructive interference at the target after propagation through a random medium.

Our experiments explore laser light intensity fluctuations, when electromagnetic spatially partially coherent MGSM beams with varying degrees of source coherence are propagated underwater in two different media scenarios: still water and water with moving entrained salt scatterers. Since, to the best of our knowledge, there are no theoretical derivations for our experimental setup, our measurement expectations are motivated on the results achieved from propagation through atmospheric turbulence [11,12]. Further, we do not claim a direct comparison between the atmospheric and underwater laser light scintillation, but simply present our observations and intuition of the measurements in the underwater conditions. Our findings support similar trends in measured scintillation for both environments, and thus suggest that the polarization diversity technique is a potentially viable performance mitigation technique in the underwater environment. We clearly observed a 50% scintillation reduction for electromagnetic beams as compared with scalar beams underwater, and this result matches the atmospheric research.

The paper is organized as follows. Beam generation is presented in Section 2. The experimental setup is discussed in Section 3. In Section 4 we describe the data analysis. In Section 5 we discuss results, and in Section 6 conclusions.

2. Beam generation

2.1. Scalar MGSM beams

In this paper we will provide a brief overview of the theory behind the generation of the MGSM [23,28–31].

The second-order correlation properties of a wide-sense statistically stationary electromagnetic beam can be described by means of the beam coherence-polarization matrix or cross-spectral density matrix [11,12] whose spatial counterparts have the same form.

A recently developed model for the MGSM (flat top) beams, gives the following spectral (scalar) degree of coherence:

$$\mu^{(0)}\left(\rho_1,\rho_2\right)=\frac{1}{C_0}\sum_{m=1}^{M}\binom{M}{m}\frac{(-1)^{m-1}}{m}exp\left[-\frac{\left|\rho_2-\rho_1\right|^2}{2m\delta^2}\right], \tag{1}$$

where ρ_1 and ρ_2 are position distances and superscript (0) refers to the source plane,

$$C_0=\sum_{m=1}^{M}\binom{M}{m}\frac{(-1)^{m-1}}{m}, \tag{2}$$

is the normalization factor used for obtaining the same maximum intensity level for any number of terms M in the summation, where $\binom{M}{m}$ is the binomial coefficient. In Eq. (1), δ is the r.m.s. width of the degree of coherence which describes the degree of coherence of the beam; where a value of $\delta = 0$ gives a spatially incoherent beam and a value of $\delta \to \infty$ gives a spatially coherent beam. Additionally, the upper index M relates to the flatness of the intensity profile formed in the far field: $M = 1$ corresponds to the classical Gaussian Schell-Model source and $M \to \infty$ corresponds to sources producing far fields with flat centres and abrupt decays at the edges.

It is important to note that we constructed the electromagnetic beams using the orthogonal components, namely vertically and horizontally polarized scalar beams are optically combined by means of interferometry. In this case the same scalar degree of coherence is used for both the vertically and horizontally polarized beams as described in Eqs. (1) and (2). Ref. [25] provides extensive details on the cross spectral density of the electromagnetic beams and provides the foundation for the construction of the electromagnetic beams used in this paper. Specifically, Ref. [25], Eqs. 19–21 provide the cross spectral density matrix of the electromagnetic Multi-Gaussian Schell Model beam.

Ref. [23] provides general details on how one uses Eqs. (1) and (2) to generate MGSM spatially partially coherent beams by using an SLM. Additionally, the SLM phase screens were created in order to shift the first order 'hot spot' off of the beam propagation path utilizing a method developed by Hyde et al. in [32–34] and further described for use with SLMs in [35].

2.2. Scintillation index of the electromagnetic beams with uncorrelated orthogonal field components

The following discussion gives a theoretical summary on calculating the scintillation index of an electromagnetic beam, [11,12,25–27,36,37]. The conventional measure of the intensity fluctuations at a single position in an optical wave is its normalized variance or the scintillation index (SI), defined as

$$SI=c\left(\boldsymbol{r}\right)=\frac{i^{(II)}\left(\boldsymbol{r}\right)-\left[i^{(I)}\left(\boldsymbol{r}\right)\right]^2}{\left[i^{(I)}\left(\boldsymbol{r}\right)\right]^2}, \tag{3}$$

where $i^{(II)}\left(\boldsymbol{r}\right)=\left\langle i(\boldsymbol{r})^2\right\rangle$ and $i^{(I)}\left(\boldsymbol{r}\right)=\left\langle i\left(\boldsymbol{r}\right)\right\rangle$ are the second and the first moment of the instantaneous intensity, $i\left(\boldsymbol{r}\right)$, and $\boldsymbol{r}$ is the position vector. As was shown in [11], the scintillation index of an electromagnetic beam may be expressed in the more general form:

$$c\left(\boldsymbol{r}\right)=\frac{c_{xx}(\boldsymbol{r})\left[i_x^{(I)}\left(\boldsymbol{r}\right)\right]^2+2c_{xy}\left(\boldsymbol{r}\right)i_x^{(I)}\left(\boldsymbol{r}\right)i_y^{(I)}\left(\boldsymbol{r}\right)+c_{yy}(\boldsymbol{r})\left[i_y^{(I)}\left(\boldsymbol{r}\right)\right]^2}{\left[i_x^{(I)}\left(\boldsymbol{r}\right)+i_y^{(I)}\left(\boldsymbol{r}\right)\right]^2} \tag{4}$$

In this representation $i_x^{(I)}$ and $i_y^{(I)}$are the mean value of intensities of x and y components of the electric field while, $c_{xx}(\boldsymbol{r})$, $c_{yy}(\boldsymbol{r})$ are the scintillation indices of the field components fluctuating in two orthogonal directions and $c_{xy}(\boldsymbol{r})$ is that for their mutual scintillation index:

$$c_{xy}\left(\boldsymbol{r}\right)=\frac{\left\langle i_x\left(\boldsymbol{r}\right)i_y\left(\boldsymbol{r}\right)\right\rangle-i_x^{(I)}\left(\boldsymbol{r}\right)i_y^{(I)}\left(\boldsymbol{r}\right)}{i_x^{(I)}\left(\boldsymbol{r}\right)i_y^{(I)}\left(\boldsymbol{r}\right)} \tag{5}$$

For uncorrelated field components, $c_{xy}(\boldsymbol{r})$ vanishes and leads to a reduction in the scintillation index compared to that for fully or partially correlated field components. In the limiting case of an unpolarized light beam, i.e., that with uncorrelated electric field components with equal intensities $i_x = i_y$, the scintillation index can be readily shown to be reduced by a factor of two, compared to an equivalent polarized (scalar) beam [11,12].

The reduction of the scintillation index was found using the following formula

$$R=\frac{\frac{c_{xx}(\boldsymbol{r})+c_{yy}(\boldsymbol{r})}{2}-c(\boldsymbol{r})}{\frac{c_{xx}(\boldsymbol{r})+c_{xx}(\boldsymbol{r})}{2}}. \tag{6}$$