Measurement of the point-spread function in a layered system

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A laboratory facility to measure the point-spread function (PSF) of water with the addition of scattering layers is described. The PSF was measured by using an approximately Lambertian source and a camera that viewed this source but focused at infinity. Measurements for various optical path lengths with the scattering layer in three separate regions, i.e., near the source, near the camera, and an intermediate case, were performed. The PSF was found to depend strongly on the location of the scattering layer. For the same optical path length, the most diffuse PSF was found for the case of a scattering layer near the camera. © 1997 Optical Society of America

1. Introduction

The viewed image of a point source of light will never be as exact or precise as the point source itself.[1] Many factors, such as refraction, lens aberrations, diffraction, and especially particle scattering, create a spreading of the source's radiant energy. This spreading, or blur distribution, defines the point-spread function (PSF) for the given medium at a specific range from the source to the image plane.

The PSF is vital in image analysis and optical oceanography for several reasons. First, the PSF can be measured *in situ*[2] and the small-angle scattering phase function can be derived from it.[3] Furthermore, the beam-spread function (BSF), which is a mathematical equivalent of the PSF,[4] models the propagation of collimated light beams in the same optical medium. Finally, the PSF can be used to describe the image of any object through a scattering medium. The determination of the PSF is fundamental to quantifying the performance of in-water optical systems.[5]

Although many measurements have been made of the oceanic point-spread function *in situ*,[6,7] almost all of these measurements have been made in near-homogeneous water columns. Although theory exists to predict how the PSF should act in a stratified medium, at least in the small-angle scattering limit[3] no experiments have been made to look at the effect of layering on the PSF. In the field, the time dependence and high variability of the water column would make measurement quite difficult in these situations; thus we set out to make measurements of the PSF in a structured water column in a controlled laboratory situation.

2. Experimental Design and Instrumentation

In these experiments, PSF measurements took place in a 1.1 m × 1.1 m × 4.0 m fiberglass optical tank. The interior was painted with black epoxy (Intertuf modified epoxy JMA413) to reduce the reflection of light from the sides and bottom of the tank. During the measurements, black neoprene material covered the water surface to eliminate reflection at the water's surface. All measurements were performed with the room lights off.

Several 1.1 m × 1.1 m Plexiglas panels were used to segment the tank physically into a maximum of five independent, nonmixing regions (See Fig. 1). The flash source and the imaging camera were suspended in the tank at a fixed separation, $R = 2.15$ m, to ensure proper alignment inside the tank. In this arrangement, the flash lamp remained in the field of view of the camera, while the walls remained well outside the camera's field of view (approximately 12° half-angle). Small minipumps (Little Giant Pump, Model 2E-N) in each segment of the tank continually mixed the water to ensure the internal homogeneity of each region. Maalox antacid was used as the particulate suspension to vary the optical path length of each region. This substance has been used in the past to simulate oceanic particulates[8] and has a scattering function that is similar to typical volume scattering functions of oceanic particulates.[9]

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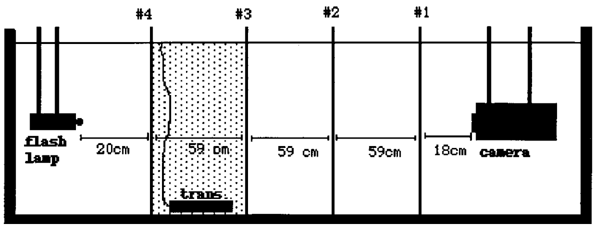

Fig. 1. Diagram of the experimental tank layout. The position of the flash-lamp source, receiving camera, and intervening Plexiglas dividers are shown; trans is the transmissometer measuring the beam attenuation in the scattering layer (in this case between separators 3 and 4, nearest the flash lamp).

The optical instrumentation used for the PSF measurement consists of two main components: a cosine emission flash lamp and a thermoelectrically cooled CCD array camera.[2] The only significant modification to the system is a 1-mm-diameter pinhole placed in front of the source to reduce its emitting area and hence be a better approximation of a point source for these short distances. In addition, a transmissometer (Sea Tech, Inc., 660 nm, 25-cm path length) was used to monitor the beam transmission, hence attenuation, of the scattering layer during the experiment.

In this experiment, the transmissometer was submerged in the turbid region of the tank in order to verify when the water reached its equilibrium point after each addition of Maalox. Transmission in the clear regions was measured both before and after a series of tests. The total optical path for the PSF measurement is the sum of the optical paths of each segment, which is given by $\tau = cl$, where l is the length of the particular segment and c is the segment's beam attenuation. Because the PSF measurements were done at 500 nm and the transmissometer data were at 660 nm, we needed to transfer the c (660 nm) to c (500 nm). This was done by subtracting the pure water absorption coefficient[10] from c (660 nm) to get the particulate c (c_p), multiplying this c_p by 1.34 (a factor experimentally determined with a multispectral transmissometer to be the spectral c dependence of Maalox), and then adding the absorption of water at 500 nm. Other than the first measurement (filtered water), the single-scattering albedo for the scattering layer was estimated to be greater than 0.90 and varied little for each case. The clear-water c was less than 0.2 m^{-1}, whereas the scattering-layer c varied from 0.6 m^{-1} to over 6 m^{-1}.

3. Data and Results

In this experiment, the PSF's were measured for five different physical situations: a clear-water calibration series with the installation of combinations of the Plexiglas panels; a homogeneous series with no Plexiglas panels, in which the entire tank was clouded with Maalox; a layered test series in which Plexiglas panels 3 and 4 were installed to create a distinct scattering region near the flash source (See Fig. 1); a layered test series in which Plexiglas panels 2 and 3 were installed to create a distinct scattering region in the center of the tank (See Fig. 1); and a layered test series in which Plexiglas panels 1 and 2 were installed to create a distinct scattering region near the imaging camera (See Fig. 1). For all of these situations, the range, R, between the source and camera was held fixed. The introduction of Maalox into the specific tank region caused a variation in the total optical path length, τ.

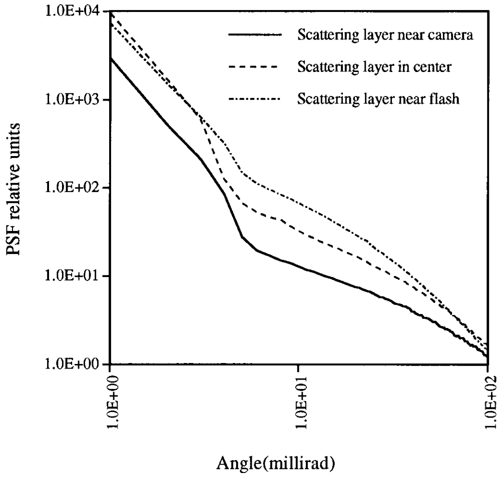

Fig. 2. Sample PSF's at $\tau = 1.6$ for each scattering layer case.

Example PSF's for $\tau = 1.6$ are shown in Fig. 2, demonstrating several basic features of all the PSF's measured in this experiment. The region from 4 to 100 mrad can be approximated by a line (particularly at large optical path lengths). This linear approximation has been found in the ocean measurements[11] and implies a very simple functional relationship for the PSF in this region: $\mathrm{PSF}(\theta) = B\theta^{-m}$, where B is a constant and $-m$ is the slope of the log(PSF)–log(θ) line.

The region of the graphs outside of 4–100 mrad are excluded for separate reasons. The small-angle zone from zero to 4 mrad, appearing as a sharp peak on the log(PSF)–log(θ) graph, is due to the physical size of the flash source.[7] At angles greater than 100 mrad, the data for the PSF often cannot be differentiated from instrument noise. This noise is typically less than one electron count per pixel. However, at angles above 100–200 mrad, the PSF data have typically fallen to approximately one count per pixel and cannot be separated from random instrument noise.[2]

For verification that the introduction of the Plexiglas panels did not perturb the PSF, an experiment was performed in which the panels were added sequentially in clear homogeneous water. The percent standard deviation of the slopes, m, in each case varied by only 0.81%; thus the Plexiglass did not introduce a significant effect on the overall PSF of the medium.

The second series of data measured the PSF for a homogeneous optical tank. In this case, all Plexiglas panels were removed from the tank and Maalox was gradually added in steps. After the Maalox suspension had time to disperse, the transmission of the water was recorded and the PSF was measured. For each of these cases, the optical path length, τ, was calculated from the

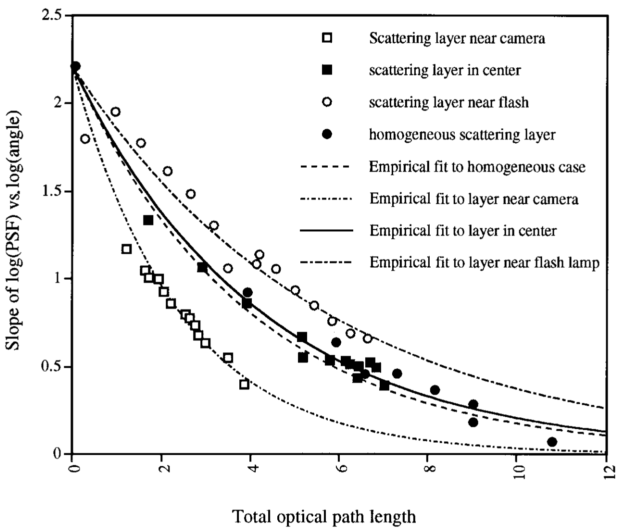

Fig. 3. Resulting slopes of log(PSF) versus log(angle) are shown as a function of optical path length, with the scattering layer in different positions. The most diffusing case, for the same path length, occurs with the scattering layer near the camera. Also shown is the empirical fit to the data in each case.

transmission values (as described above). Figure 3 shows the plot of the slope of the PSF versus the optical path length for the homogeneous case.

An analytical equation was fit to the PSF data in each case (layering and optical path length). This equation took the form $m = W \times 10^{-\beta\tau}$. This form has been found to fit the PSF data in other cases[11] and allows us to simply parameterize the variation of the slope of the PSF in terms of the two constants, W and β. As we can see in Fig. 3, this form also fits the data from this layered case. Because each case started out similarly, W (the value of m for $\tau = 0$) should be the same for all cases. Thus the fit constrained W to be a value of 2.209 (the largest m measured).

All three layered test series were handled in a similar way. After the appropriate Plexiglas panels were in place, Maalox was added to the small scattering region in gradual steps. The transmission for the scattering region was recorded after each addition of Maalox, and the PSF was measured. Figure 3 illustrates the $m - \tau$ curves for the cases with the region near the flash, in the center, and near the camera. The fitted curves are shown in Fig. 3, and the exponent factor, β, was found to be 0.110, 0.077, 0.103, and 0.182 for the homogeneous case, layer near the flash, layer in middle, and layer near the camera, respectively. The percent standard deviations of these estimates were 5%, 6%, 3%, and 2%, respectively.

Note that the values of β varies systematically for the layered cases. As the scattering region moves away from the flash and toward the camera, β increases steadily. Thus the PSF of the water depends strongly on the location of the scattering region as well as the overall optical path length. For a given optical path length, the slope of the PSF is greatest if scattering occurs near the flash and smallest if scattering occurs near the camera. Also note that the PSF for the homogeneous case was not significantly different than that for the case with the scattering layer in the center.

These qualitative differences in the PSF's for layered media are reasonable results that can be explained quite well by analogy.[3] Suppose a printed page is seen through a thin piece of tissue paper. If the tissue paper is placed directly on top of the page, the print can still be read quite easily. If instead the same tissue paper is held directly in front of the eyes, the printed page is completely obscured. Likewise, the location of the scattering region in the layered optical tank affects the image of the PSF. Scattering that occurs nearest the flash source leads to a highly sloped PSF. That is, the camera images the flash source with only small blurring. In contrast, scattering that occurs closest to the camera creates a PSF with much smaller slope. The smaller slope implies that this image of the flash source has been blurred more significantly. Finally, scattering in the intermediate region creates PSF's with intermediate slope.

This experiment provides the first laboratory data for optical media comprising distinct scattering layers. This demonstrates that a strong inhomogeneity of the water column can have a significant impact on the measured PSF. In the future we plan to compare these measurements with small-angle scattering theory[3] to see if these effects can be modeled quantitatively.

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