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14. ABSTRACT

Optical signal transmission underwater is of vital interests to both civilian and military applications. The range and signal to noise during the transmission, as a function of system and water optical properties determines the effectiveness of EO technology. These applications include diver visibility, search and rescue, mine detection and identification, and optical communications. The impact of optical turbulence on underwater imaging has been postulated and observed by many researchers. However, no quantative studies have been done until recently, in terms of both the environmental conditions, and impacts on image quality as a function of range and spatial frequencies. Image data collected from field measurements during SOTEX (Skaneateles Optical Turbulence Exercise, July 22-31, 2010) using the Image Measurement Assembly for Subsurface Turbulence (IMAST) are presented. Optical properties of the water column in the field were measured using WETLab's ac-9 and Laser In Situ Scattering and Transmissometer (LISST, Sequoia Scientific), in coordination with physical properties including CTD (Seabird), dissipation rate of kinetic energy and heat, using both the Vector velocimeter and CT combo (Nortek and PME), and shear probe based Vertical Microstructure Profiler (VMP, Rockland). The strong stratification structure in the water column provides great opportunity to observe various dissipation strengths throughout the water column, which corresponds directly with image quality as shown. Initial results demonstrate general agreement between data collected and model prediction, while discrepancies between measurements and model suggest higher spatial and temporal observations are needed in the future.

15. SUBJECT TERMS

visibility, scattering, particles, turbulence, underwater imaging, MCM, OTF, MTF

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Impacts of optical turbulence on underwater imaging

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ABSTRACT

Optical signal transmission underwater is of vital interests to both civilian and military applications. The range and signal to noise during the transmission, as a function of system and water optical properties determines the effectiveness of EO technology. These applications include diver visibility, search and rescue, mine detection and identification, and optical communications. The impact of optical turbulence on underwater imaging has been postulated and observed by many researchers. However, no quantative studies have been done until recently, in terms of both the environmental conditions, and impacts on image quality as a function of range and spatial frequencies. Image data collected from field measurements during SOTEX (Skaneateles Optical Turbulence Exercise, July 22-31, 2010) using the Image Measurement Assembly for Subsurface Turbulence (IMAST) are presented. Optical properties of the water column in the field were measured using WETLab's ac-9 and Laser In Situ Scattering and Transmissometer (LISST, Sequoia Scientific), in coordination with physical properties including CTD (Seabird), dissipation rate of kinetic energy and heat, using both the Vector velocimeter and CT combo (Nortek and PME), and shear probe based Vertical Microstructure Profiler (VMP, Rockland). The strong stratification structure in the water column provides great opportunity to observe various dissipation strengths throughout the water column, which corresponds directly with image quality as shown. Initial results demonstrate general agreement between data collected and model prediction, while discrepancies between measurements and model suggest higher spatial and temporal observations are needed in the future.

Keywords: visibility, scattering, particles, turbulence, underwater imaging, MCM, OTF, MTF

1. INTRODUCTION

When it comes to diver visibility, the most prominent issue is the degradation of image quality over distance due to attenuation. This presents a striking contrast for us who are used to the seemingly unlimited visual ranges in air. The cause of the degradation has been mostly attributed to the dirt, or particles in the water and it is rightly so. Most research have been focusing on reducing the impact of particle scattering by means of discriminating scattering photos involving polarization, range gating, modulation, and by means of restoration via deconvolution [1-6]. However, in clean oceanic or lake waters, another factor could come into play. This is the scattering by optical turbulence, which is the result of the variations of the index of refraction of the medium. This is mostly associated with the turbulence structures of the medium, or water body in our case. Degradation of the image quality in a scattering medium involving turbulence has been studied mostly in atmosphere. These studies are mainly focused on modeling the optical transfer function, in an effort to restore the images obtained, such as in air reconnaissance or astronomy studies [7, 8]. Little has been done regarding the turbulence effects on imaging formation in water, mainly due to the dominant particle scattering and strong attenuation associated. This is of little surprise as anyone with experiences in coastal waters, especially those inside a harbor, or estuary areas like Mississippi, experience first-hand looks of how visibility could quickly reduce to zero in a matter of a few feet. The same applies to regions of strong re-suspensions from the bottom, both in coastal regions as well as in the deep sea. However, the effects of turbulence have been postulated to have impacts over long image transmission range [9], which has been supported by light scattering measurements and simulations [10]. Under extreme conditions, observations have been made that involves targets with a pathlength of a few feet [11]. The images obtained under such conditions are often severely degraded or blurred, on par or more than those caused by particle scattering. Overcoming such challenges to increase both the reach and the resolution is of vital importance to military and civilian applications, from mine detection and identification, to diver visibility, undersea communications, and search and rescue operations. It is important to establish a good understanding about the limiting factors under different

conditions. SUIM [12] was developed to address this issue and it has been shown that on average, the relative contribution of different components [3, 13] in underwater imaging applications can be expressed in terms of the optical transfer function (OTF) as

$$OTF(\psi,r)_{total} = OTF(\psi,r)_{path}OTF(\psi,r)_{par}OTF(\psi,r)_{tur}$$

$$= \left(\frac{1}{1+D}\right)\exp\left[-cr + br\left(\frac{1-e^{-2\pi\theta_0\psi}}{2\pi\theta_0\psi}\right)\right]\exp\left(-S_n\psi^{5/3}r\right) \qquad (1)$$

$$= \left(\frac{1}{1+D}\right)\exp\left\{-\left[c - b\left(\frac{1-e^{-2\pi\theta_0\psi}}{2\pi\theta_0\psi}\right) + S_n\psi^{5/3}\right]r\right\}$$

where θ_0 relates to the mean scattering angle, c and a are the beam attenuation and absorption coefficients respectively. Ψ is the spatial frequency in cycles per radian, r is the imaging range, and D relates to path radiance [3]. S_n contains parameters that are dependent on the structure function and which can be further expressed in terms of turbulence dissipation rate of temperature, salinity and kinetic energy, assuming Kolmogorov power spectrum type. The above model has been validated using indirect measurements using field data, without involvement of precise turbulent measurements, nor with a stable imaging platform to obtain underwater imagery. Here we present the first results of a recent field exercise and efforts associated with the model validation. Since the phase information can be ignored under incoherent imaging conditions, the magnitude of the OTF or the modulation transfer function (MTF) will be used interchangeably here.

2. EXPERIMENT SETUP

Optical turbulence underwater is primarily a function of temperature structure, although salinity variations could at time contribute to strong optical turbulence [11]. Intensified thermoclines in natural environments provide a convenient setup to examine this chaotic process. We identified one of the finger lakes in upstate New York, Skaneateles, as our test site for SOTEX (Skaneateles Optical Turbulence EXercise, July, 2010). Figure 1 shows the approximate location of the two stations, the first (S1, red circle) near the center of the lake (42.8668° N, 76.3920° W) over a sloping bottom with an approximate depth of 70m, the second (S2, blue triangle) at the northern end of the lake (42.9063° N, 76.4058° W) over a flatter bottom with an approximate depth of 50m. The lake is the clearest of all finger lakes, with an average Secchi depth near 8m [14], and allowing for imaging under varied turbulent strength, while with little scattering contribution from particulates. The strong stratification in July at relatively shallow depth, and less wind and current interference ensure a well-defined thermocline, as demonstrated by the temperature profiles shown in Figure 2, measured by a Seabird CTD. The same features help to form strong structures for optical turbulence in the lake. The optical properties of the water column were measured by a 9-channel absorption and attenuation meter (ac-9, by WETLabs), and Laser In Situ Scattering Transmissometer (LISST, Sequoia Scientific). We notice that the water in the top part of the water column, just above the sharp thermocline is rather clear, with beam attenuation at 532nm valued below 0.4m^{-1}, before increasing sharply (Fig.2). Turbulence measurements of the water column were carried out by a Vertical Microstructure Profiler (VMP, by Rockland Scientific), a 3D velocimeter made by Nortek (Vector), with fast conductivity and temperature probes (CT) made by PME. These two different measurement approaches, namely the shear-probe-based, and acoustical-Doppler-based, converge on most occasions. The details can be found in a separate paper in this volume [15].

In order to estimate the effects of the optical turbulence in the water column, it is essential to remove any other variations that could contribute to the blurring of the imagery obtained. For this reason, the Image Measurement Assembly for Subsurface Turbulence (IMAST) was designed and implemented at NRL. The camera and housing, passive and active imaging targets are attached to the 5m aluminum structure, along with the Vector, and CTD. A separate optical profiler frame containing the optical sensors discussed above is deployed in close vicinity of IMAST, under the assumption of homogeneity. It is worth mentioning that the Vector is also deployed with the optical package on a smaller frame facing outside, in an effort to compare with the VMP [15]. Standard (USAF-1951) and custom-

made resolution charts are used, with different spatial frequencies. A high speed imaging camera is used to record images at various frame rate, up to 300 fps at 500x400 pixels, and higher resolution with reduced frame rates. IMAST is deployed in two configurations in the water column, vertical and horizontal. In the vertical mode, the IMAST is lowered and stay stationary such that the entire thermocline is within the imaging range. In the horizontal mode, the frame is suspended in the water column, in the middle of, above and beneath, the thermocline, for extended periods of time, in order to accurately quantify the turbulence environment. The details of the setup and measurement can be found in the previously mentioned companion paper [15]. It is understandable that the IMAST would introduce drag and affect turbulence flow. However, since we are measuring the turbulence in situ, along the imaging path, it should not introduce errors to bias our validation. A pair of sample images are shown in Figure 4. They are taken from two different depths, one at 2.8m which is essentially free of optical turbulence, while the one at 8.7m is strongly influenced by optical turbulence. Both are taken under the horizontal deployment configuration. One can notice that despite of the similar optical properties measured (Fig.2), the one inside the strong turbulence layer (lower) suffered much more degradation, compared to the weaker turbulence situation (top). The turbulence dissipation rate ranged from very low values up to 10^{-6} $m^2 s^{-3}$ at the highest for kinetic energy, and 10^{-6} $^{O}C^2/s$ for temperature.
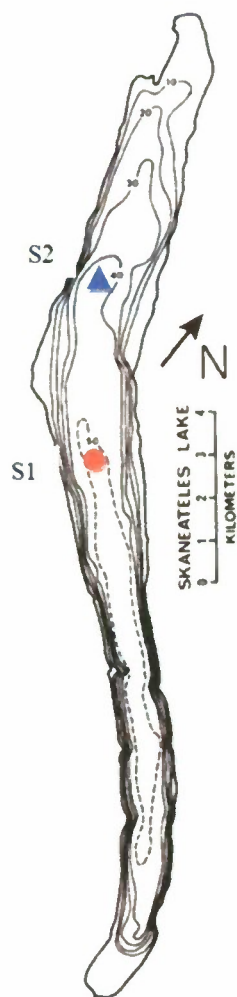

Figure 1. Bathymetric sketch of Skancateles Lake showing the approximate location of the two stations: S1 (red circle) near the center of the lake, and S2 (blue triangle) in the northern end of the lake. Map from http://www.ourlake.org/html/skaneateles_lake1.html.
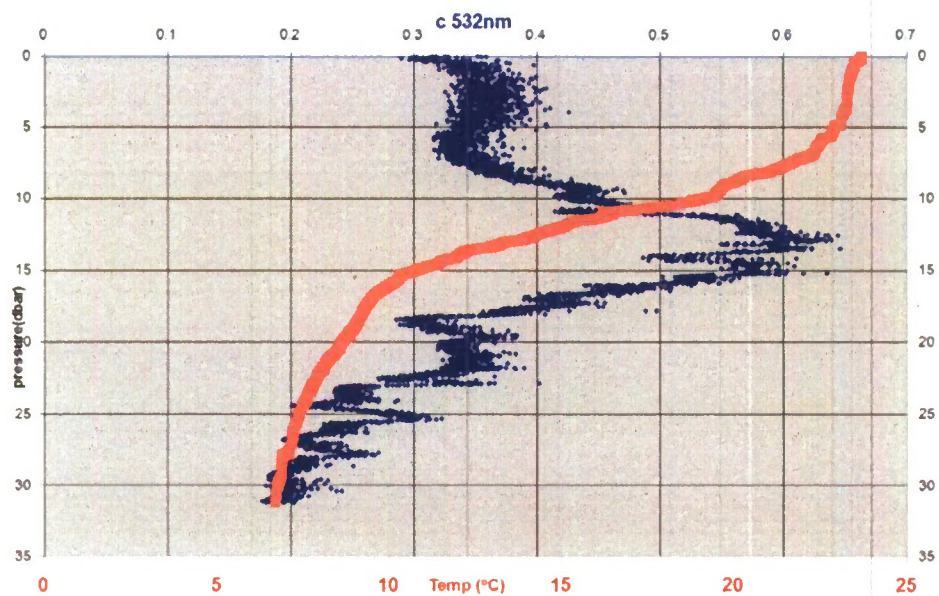
Figure 2. Temperature (solid line) and beam attenuation (dots) profile measured during SOTEX deployment. Vertical units are equivalent to meters. Beam attenuation coefficients are in m^{-1}. Notice strong particle layer at the bottom of the strong thermocline.

Figure 3. Picture of IMAST during SOTEX deployment. Notice the camera in the housing (bottom of the picture) and passive resolution target at the far end of the IMAST.

3. RESULTS AND DISCUSSION

From images obtained at different depths, corresponding to different turbulence conditions, one can estimate the image degradation in terms of MTF, which describes the total system response at different spatial frequencies. There are many methods to derive MTF from imagery. For our initial results, we estimated the MTF using a standard slant edge technique [16, 17]. The results are shown in Figures 5 and 6 below. Notice that a pristine image is obtained in lab for reference only, over the same pathlength with filtered water, clear of particle scattering effects. The MTFs are estimated using the same region of interests (ROI) of consecutive frames, for single and averaged results (10 frames). These are obtained from active source (one way path) during night deployment, to minimize path radiance. It is understandable that averaging would result in more degradation on images suffering from stronger turbulence impacts (lower, Fig.4), than those from less turbulence (upper image, Fig.4). It is worth noting that only one ROI is used in processing the imagery, which should explain the unusual behavior at the high spatial frequency end of the spectra. The signal to noise ratio (SNR) cannot be improved, when multiple frames are used, as each individual frame would typically undergo a different amount of degradation. Therefore the averaging would only increase the SNR towards the low frequency elements, and leave behind random variations at the high frequency end. This is necessary, however, in order to contain all of the variations caused by the optical turbulence [12].
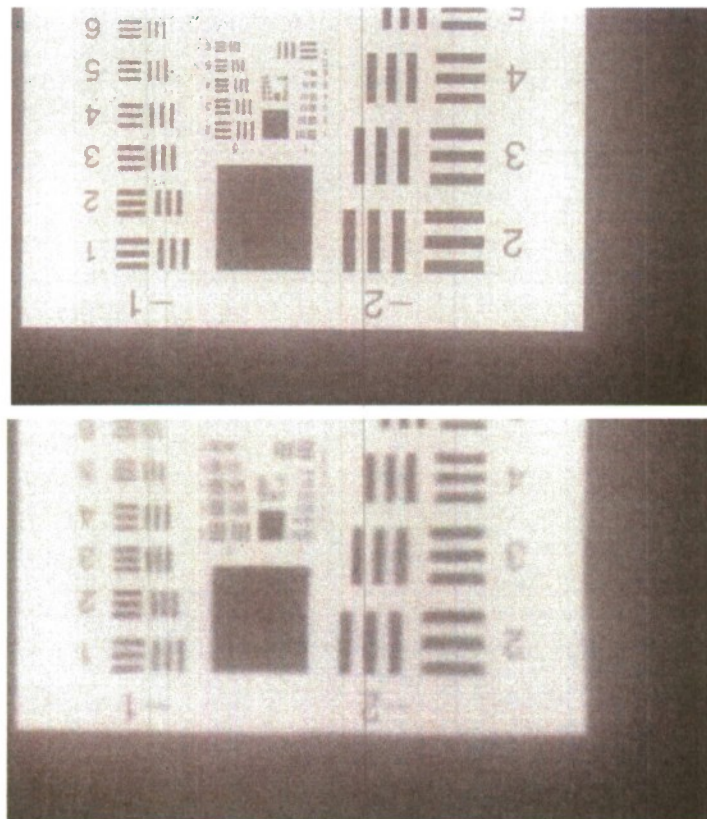

Figure 4. Images taken by IMAST during SOTEX at 2.8m (top) and 8.7m (bottom), in conditions corresponding to those from Fig.2. Notice the impact of optical turbulence alone on the image degradation, when the amount of particle scattering is comparable (beam attenuation under $0.4m^{-1}$).

Recall the SUIM model discussed in the previous section, one estimate the impacts from optical turbulence using the measurements from the VMP and Vector. This is shown in Figure 6, when the assumption can be made that the difference in MTFs at the different depths is primarily the result of turbulence structure. By applying kinetic energy dissipation rate of 10^{-9} m^2s^{-3}, and temperature dissipation rate of 10^{-7} $°C^2/s$, one can see that the model result

approximates the field measurements reasonably well. The differences between the model and measurements can be explained by multiple factors. The primary reason should be the difference in measurement scales in the temporal domain. This is troublesome, especially when spatial fluctuations of the turbulent flow cannot be treated as isotropic and statistically homogenous. More rigorous post-processing of images involving multiple ROIs, and direct derivation of MTFs using the whole resolution pattern should help to improve the results.
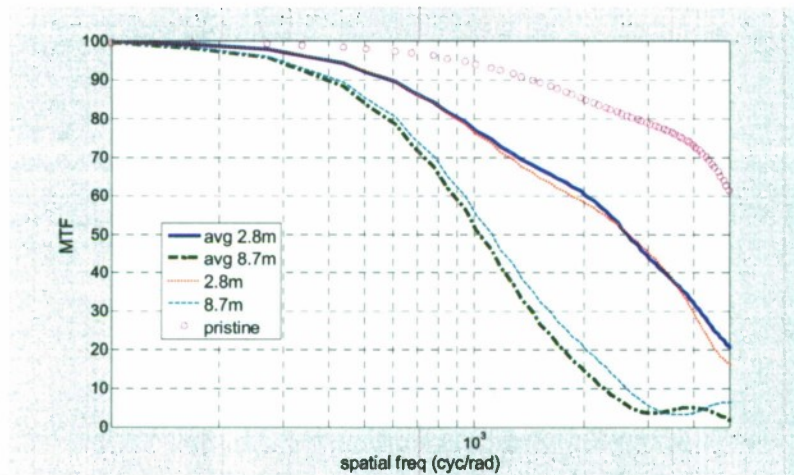

Figure 5. Normalized MTF of individual and averaged images obtained under strong (8.7m) and weak (2.8m) optical turbulent environment during SOTEX. MTFs are calculated using slant edge algorithms over same ROI for all images. The optical properties of these images correspond to those shown in Fig.2
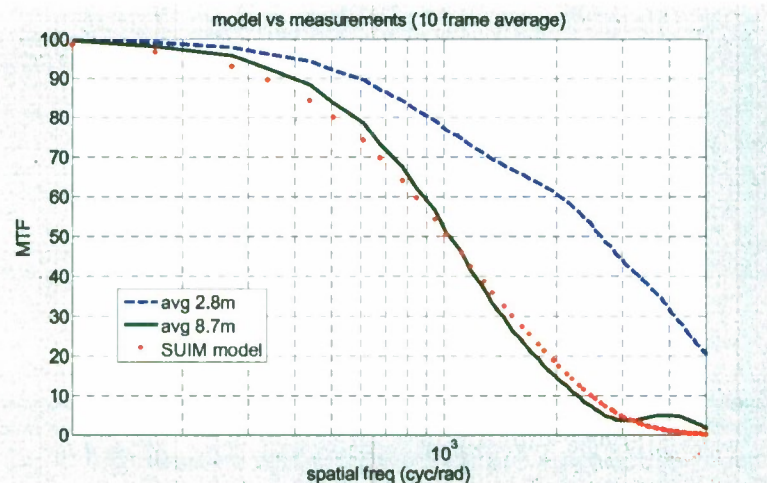

Figure 6. MTF comparison between measured at 8.7m and modeled at the same depth, using measured MTF at 2.8m and combined with SUIM model to account for turbulence impacts. See text for details.

4. CONCLUSION

The impact of optical turbulence on imaging is directly measured in the field for the first time during our SOTEX exercise in July 2010, along with optical properties and turbulence dissipation rate. This paper validates previously

developed SUIM model with direct field measurements. Our initial results show that directly measured MTF over turbulent flow from the field matches well with model derived MTF, based on Kolmogorov power spectrum. Further validation of the theory is necessary, especially under different turbulence conditions and particulate concentration. The application range of the developed theory should also be tested, along with different turbulence models and subregimes.

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