REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 08-08-2016	**2. REPORT TYPE** Journal Article	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Optical Turbulence in the Ocean (invited)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0602435N

6. AUTHOR(S)
Weilin Hou

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
73-4951-05-5

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/JA/7330--15-2537

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
One Liberty Center
875 North Randolph Street, Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The established view of diver visibility has been mainly focused on the effects of particles or turbidity of the water. The influence of optical turbulence due to variations of ocean temperature and salinity is shown to contribute to the degradation, through model and field validation. Lab setup of a simulated environment and future directions are also discussed.

15. SUBJECT TERMS
Visibility and imaging; Ocean optics; Turbulence

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Weilin Hou
Unclassified	Unclassified	Unclassified	UU	03	**19b. TELEPHONE NUMBER** *(Include area code)* (228) 688-5257

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15-1231-1322

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Route Sheet No. 7330/
Job Order No. 73-4951-05-5
Classification U ____ S ____ C
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4. AUTHOR

Title of Paper or Presentation
Optical Turbulence in the Ocean

AUTHOR(s) LEGAL NAMES(s) OF RECORD (First, MI, Last), CODE, (Affiliation if not NRL).
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This paper will be presented at the OSA Imaging and Applied Optics Meeting
(Name of Conference)

07-JUN - 11-JUN-15, Arlington, VA, Unclassified
(Date, Place and Classification of Conference)

and/or for published in OSA Imaging and Applied Optics Meeting, Unclassified
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Section Head			
Branch Head Richard L. Crout, 7330		4-8-2015	
Division Head Ruth H. Preller, 7300		4/9/15	1. To the best knowledge of this Division, the subject matter of this publication (has ____)(has never ____ Xbeen classified. 2. This paper (does ____) (does not __ X) contain any militarily critical technology.
ADOR/Director NCST E. R. Franchi, 7000			
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Associate Counsel,Code 1008.3	supercede invention memo	5-7-15	
Public Affairs (Unclassified/ Unlimited Only), Code 7030.4	Shannon Mensi	4-27-15	
Division, Code			
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HQ-NRL 5511/6 (Rev. 12/14) THIS FORM CANCELS AND SUPERSEDES ALL PREVIOUS VERSIONS

Optical Turbulence in the Ocean (invited)

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Abstract: The established view of diver visibility has been mainly focused on the effects of particles or turbidity of the water. The influence of optical turbulence due to variations of ocean temperature and salinity is shown to contribute to the degradation, through model and field validation. Lab setup of a simulated environment and future directions are also discussed.
OCIS codes: (010.7295) Visibility and imaging; (010.4450) Ocean optics; (010.7060) Turbulence

1. Introduction

Researchers of light transmission in the ocean have been long aware of the impact of optical turbulence on the signal transmission. While some might disagree with the term, as it is not the source of the turbulence, but rather the influences of temperature and/or salinity variations of the microstructures in the ocean, the effects have been observed and postulated to be mainly forward dominant. Classical works by several AGARD lecturers, such as Wells [1] discussed their impacts. Field demonstration showed that under extreme conditions, the degradation on image quality by optical turbulence can overtake that of turbidity [2]. Numerical simulations of small turbulence tank (30cm) also showed that the forward scattering can be orders of magnitude higher than the particle scattering, particularly in open oceans [3]. Efforts have been put in to quantify the turbulence process itself, by examining the scattering properties using existing sensor arrays such as wavefront sensor [3], although few quantative results are available, to link the level of turbulence intensity to the optical signal transmission intensity. Directional change of polarization states have been examined in theory [4] and experiments [5], as a function of turbulence intensities, although concurrent measurements and model is still missing. Borrowing techniques from atmospheric turbulence research, we developed a theoretical model based on the modulation transfer function of the medium and turbulence, and subsequently validated by field efforts, which is discussed in Section 2. To better quantify this stochastic process, and develop means of mitigation, a controlled lab environment has been setup, to simulate various optical turbulence intensities by using a Rayleigh-Bénard convection tank. The tank is capable of generating and maintaining turbulence with Kolmogorov-type energy dissipation spectrum, as shown in Section 3. The tank setup has been guided by both numerical experiment using Large Eddy Simulation model, and measurements using acoustic Doppler velocimeter (ADV), and faster temperature probes. However, issues are abundant and require better lab measurements. A new type of sensor is under development and initial results are presented in Section 4.

2. SUIM and field validation

Little has been done in terms of quantifying the influence of underwater optical turbulence to signal transmission. A simple underwater imaging model (SUIM) was developed[6], based on similar approach from atmospheric optics, incorporating factors affecting the index of refraction (IOR) due to microstructure variations caused by temperature or/and salinity fluctuations in the ocean. Optical Transfer Functions (OTF), or Modulation Transfer Functions (MTF), are used when phase information is not a factor, to quantify the impacts from turbulence. Briefly, the combined effects from both turbidity and turbulence can be written as [6]

$$\begin{aligned} OTF(\psi,r)_{total} &= OTF(\psi,r)_{path}\,OTF(\psi,r)_{par}\,OTF(\psi,r)_{tur} \\ &= \left(\frac{1}{1+D}\right)\exp\left[-cr+br\left(\frac{1-e^{-2\pi\theta_0\psi}}{2\pi\theta_0\psi}\right)\right]\exp\left(-S_n\psi^{5/3}r\right) \\ &= \left(\frac{1}{1+D}\right)\exp\left\{-\left[c-b\left(\frac{1-e^{-2\pi\theta_0\psi}}{2\pi\theta_0\psi}\right)+S_n\psi^{5/3}\right]r\right\} \end{aligned} \qquad (1)$$

where S_n=1736$K_3\lambda^{-1/3}$, and the K_3=$B_1\chi\varepsilon^{-1/3}$. Ψ is the angular spatial frequency Ψ and r is the transmission range. b, θ_0 and c are the scattering coefficient, mean scattering angle and beam attenuation coefficient, respectively. D is the normalized radiance, and the first term describes the effects of the path radiance. Utilizing Image Measurement

Assembly for Subsurface Turbulence (IMAST), we validated the above model during Skaneateles Optical Turbulence Experiment (SOTEX, [7]), and Bahamas Optical Turbulence Experiment (BOTEX, [7-9]).

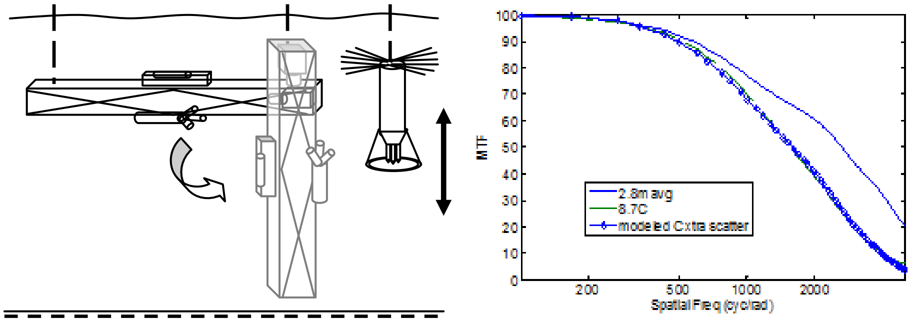

Figure 1. Validation of SUIM. Left: field setup; Right: compared measurement to model results. Details see Hou et al, 2012.

3. Simulated Turbulence Environment

One of the main obstacles in studying turbulence is the stochastic nature of the process. In order to have a more controlled setting, we set up a simulated environment using a Rayleigh-Bénard (RB) convection tank (Fig.2). Heating and cooling are realized by two stainless steel plates with fluid flowing through at a preset temperature inside.

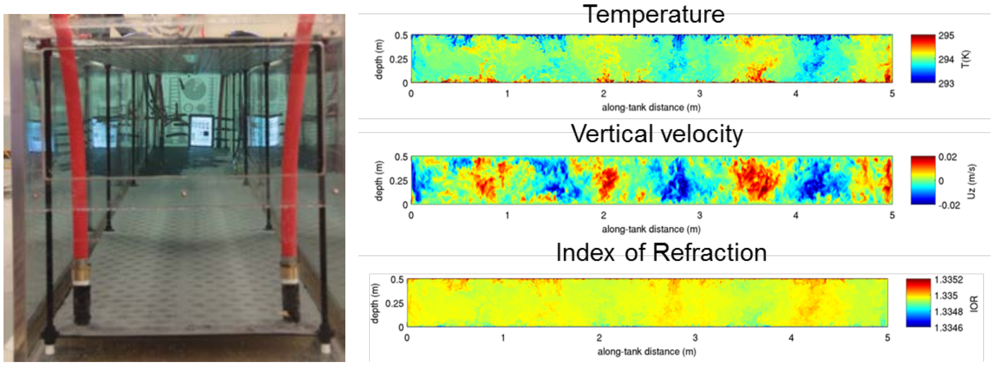

Figure 2. Rayleigh-Bénard convective tank setup (left) and numerical simulation results (right).

While the process itself can be seen actively generate turbulence, it is important to examine the energy dissipation scheme to ensure the setup follows naturally occurring mixing, such as the Kolmogorov type. Our analysis confirms such behavior, as shown in Fig. 3 ([10]).

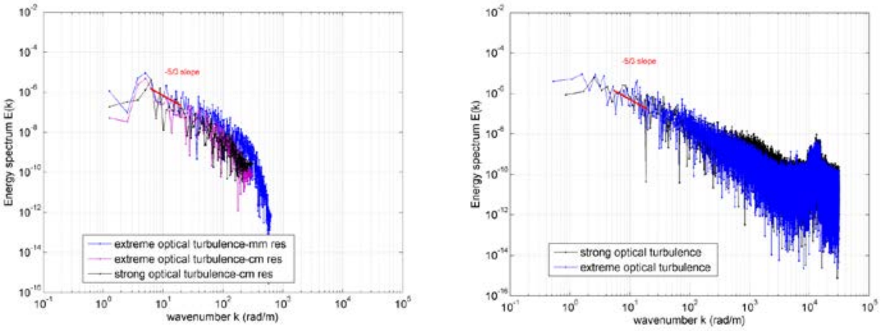

Figure 3. Numerical model spectrum (left) and measurement results (right) confirms Kolmogorov spectrum slope of -5/3.

4. Better Sensing Capability

One of the issues quantifying the optical turbulence underwater is the difficulty obtaining high-speed, high-resolution data associated with the process. To overcome such challenge, we developed a novel temperature sensor, capable of 1khz sampling with 1/1000 ^{o}C accuracy[11]. This is based on a fiber optics sensor head, using a silicon pillar attached to the end of the fiber. Figure 4 depicts the actual sensor and measurement from our RB tank.

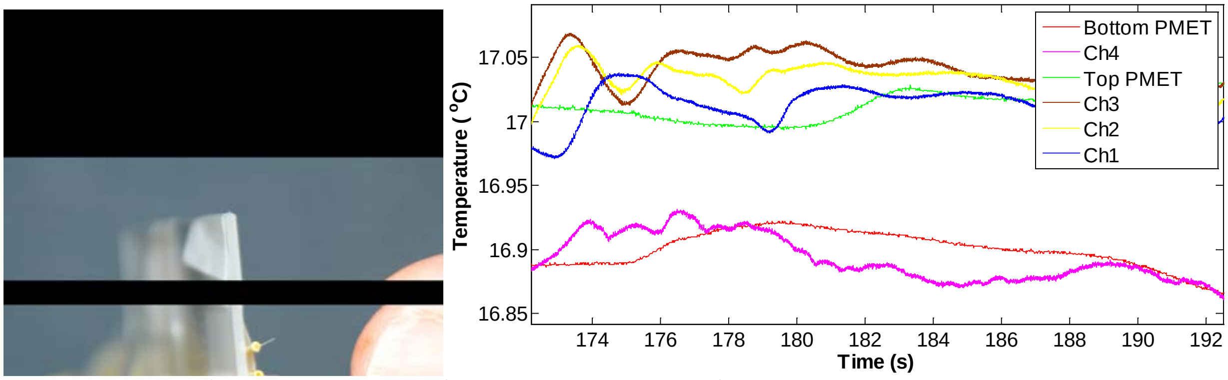

Figure 4. A new novel fiber temperature sensor (left) and the measurement results from the RB tank, compared to two FP07s (marked "PMET"). Fiber sensors (ch1 -4) are placed within 5mm to nearby FP07.

5. Summary

We present a quick summary of optical turbulence research in the ocean, along with new modeling and measurement approach to mitigate the impacts on optical signal transmission. A quantified model can be used to estimate the optical turbulence vs turbidity on image degradation in the ocean. A simulated environment can be used to better examine the stochastic process, and means to mitigate such influence. Finally, a new thermometer is developed to better quantify the small scale fluctuations.

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