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Effects of Natural, Undisturbed Particle Fields on Light Transmission and Dispersion in Coastal Waters

Michael Twardowski and James Sullivan
Harbor Branch Oceanographic Institute, Florida Atlantic University
5600 US 1 N
Ft. Pierce, FL 34946
phone: (772) 242-2220 fax: (772) 466-3644 e-mail: mtwardowski@fau.edu

George Kattawar
Institute for Quantum Science and Engineering, Texas A&M University
College Station, TX 77843-4242
phone: (979) 219-7767 fax: (979) 458-7931 e-mail: Kattawar@tamu.edu

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LONG-TERM GOALS

Our long-term goal is to better understand the effects of natural particle dynamics on the underwater light field and associated applications such as imaging, lidar, and remote sensing. Effects from layering of particles, preferential particle orientation in the water column, complex particle structures and shapes, and particle aggregation are of particular interest. A long-term goal is to employ custom, innovative technologies to explore aspects of these relationships that have not previously been resolved.

OBJECTIVES

Our goal is to assess effects of naturally occuring, nonrandom particle orientation on light propagation in coastal waters, with the following 3 objectives:

1) Gather both empirical and quantitative evidence showing that the *in situ* orientation of sensors measuring particle scattering can affect resultant values because of naturally occurring preferential particle orientation in the water column;
2) Gather statistical distributions from a custom *in situ* holographic video microscope detailing the spatial orientation of undisturbed particles in the water column, collected concurrently with the measurements needed for Objective 1; and
3) Conduct modeling studies of light propagation using the particle size, shape, structure, and non-random orientation statistics gathered for Objective 2, and compare to models using the same particle size populations in random orientation and to the instrument measurements gathered for Objective 1.

APPROACH

The approach addressing Objective 1 relies on optical scattering sensors making measurements in undisturbed remote volumes. Multiple sensors resolving measurements such as the volume scattering function and attenuation with the same optical geometry, but in different orientations in adjacent sample volumes, should read approximately the same if the particle field is completely randomly oriented. If particles are preferentially oriented, then different scattering and transmission values are expected. Key sensors for this analysis will be two custom Multi-Angle SCattering Optical Tool (MASCOT) sensors measuring the volume scattering function (VSF) between 10 and 170 degrees in undisturbed, remote volumes (Twardowski et al. 2012). Polarizers will also be used to resolve polarized scattering parameters that are sensitive to particle orientation. Simultaneous deployment of multiple, matching sensors spatially separated but in the same orientation will provide statistics on the natural spatial variability of the optical parameters, distinct from any orientation effects. Because the sampling platform will be designed to profile downward through the water column, the sample volumes for all the sensors will resolve scattering in different azimuthal directions within the same horizontal plane near the bottom of the profiling cage to ensure sample volumes are undisturbed.

Concurrent documentation of particle orientations and shapes for Objective 2 will be carried out with a custom *in situ* holographic video imaging system (HOLOCAM), able to assess particle fields in undisturbed remote sample volumes. Any preferential particle orientation can be documented unambiguously with HOLOCAM, and then compared to any deviations found between matching optical scattering sensors in different orientations. HOLOCAM is being deployed adjacent to a Nortek Vector ADV and Aquadopp to parameterize current velocities, shear and turbulence coincident with particle observations.

The final objective is to model light scattering properties of dominant particle types exhibiting preferential orientation from field work to show theoretically what the expected variability in realized scattering should be for light impinging at different incident angles. Such results can be compared with *in situ* scattering measurements. The arsenal of computational tools for doing this consists of the following codes currently employed by George Kattawar's team: a) the ADDA (Amsterdam Discrete Dipole Approximation) code, recently developed and released at the University of Amsterdam (Yurkin & Hoekstra, 2011), shows superb performance for light scattering for a particle whose refractive index is close to unity; b) for larger homogeneous particles, an improved geometric optics method (Bi et al., 2011) shall be employed to calculate the light scattering properties; c) if the particles are large and inhomogeneous, a new method called the "invariant imbedding method (Bi et al., 2012) will be employed, based on using a combination of a volume integration method coupled with a T-matrix approach; and d) for chain-like particles such as diatoms, a new method based on the Extended Boundary Condition Method (EBCM) (Yan et al., 2008) has been developed, whereby knowing the solution for a single element in the chain, the exact solution for the chain can be calculated.

WORK COMPLETED

Some logistics: contract originally through WET Labs was transferred to HBOI-FAU. Transfer to HBOI-FAU allowed hire of 2 postdocs, partially supported by research pertaining to this project. All equipment associated with the project was also transferred to HBOI-FAU in the summer of 2015. The project grant was activated at HBOI-FAU 9/14/15. Preparations for our primary field experiment for the project in East Sound, WA started throughout the summer and the experiment itself was held 9/7/15 to 9/25/15 in collaboration with NRL SSC. Other funds were leveraged for the preparations.

The deployment cage for the experiment, developed to vertically profile optical sensors without disturbing water sample volumes, was designed, built, and tested at HBOI in August 2015 (**Fig. 1**).

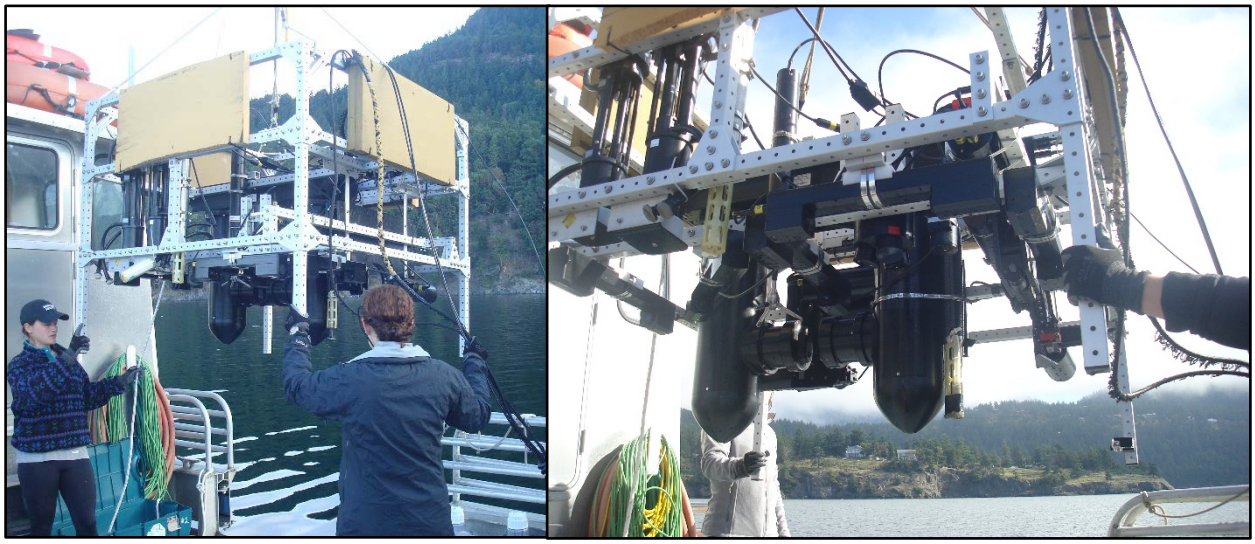

Figure 1. Left panel showing 4' X 4' X 3.5' instrumentation package being deployed in East Sound, WA. Right panel shows close up view of the underside of the package with the sensors. All sample volumes for all sensors were in the same horizontal plane. Sensors included 2 MASCOT VSF devices in orthogonal relative orientation, holographic video microscope, 5 WET Labs c-stars (transmissometers) in different orientations, 2 WET Labs ac9 devices, SBE CTD, Nortek Vector ADV, and Nortek Aquadopp.

The sensor package was vertically profiled throughout East Sound 9/11/15 to 9/23/15 with several other optical sensing systems provided by colleagues led by Alan Weidemann at NRL and Fraser Dalgleish at HBOI, including two lidar systems, an imaging flow cytometer, and an above-water polarimeter. Our group also deployed a separate package testing *in situ* absorption sensors that included the WET Labs ac9 and Turner Designs ICAM.

Postdoc Aditya Nayak began a study on the small scale physics associated with water column locations where preferential particle orientation is observed. Dr. Nayak mounted the ADV and Aquadopp sensors for the East Sound deployment, collected data, and is starting analysis. Dr. Nayak also started development on a model simulating particle orientation for different types of particles in various flow regimes, initially based on the model of Jeffrey (1922).

Postdoc Malcolm McFarland assisted in operation of the HOLOCAM and other equipment and began development of a model to assess changes in particle absorption from particle fields in different orientations. HOLOCAM data collected in 2013 from East Sound helped to provide input to the model.

TAMU Postdoc Bingqiang Sun lead-authored a submitted paper on modeling scattering by chain-forming diatoms, with cell and chain dimensions based on field data collected with the HOLOCAM in East Sound in 2013. Several simulations were also carried out to assess the effects of oriented chains, which is currently being worked into a subsequent publication.

RESULTS

Particle fields concentrated into dense layers associated with strong pycnoclines and layers of shear were again observed during the September 2015 deployment in East Sound, WA. A strong thin layer was observed 9/22/15, ca. 25 cm full-width-half-max intensity in attenuation, oscillating with internal waves between ca. 2 to 4 m in depth (**Figs. 2-4**). Preliminary absorption spectra in the peak showed pigment signatures consistent with diatoms (**Fig. 4**). Attenuation spectra in the peak showed unusual deviation from a power law shape in the red part of the spectrum, presumably related to an anomalous dispersion effect associated with the strong chlorophyll absorption centered at 676 nm and the specific size dimensions and packaging effects of the dominant phytoplankton.

The intense thin layer was also observed remotely with the NRL above-water lidar system, collecting data continuously during our profiling (**Fig. 5**).

HOLOCAM images within the peak showed systematically orienting diatom chains dominated by the genus *Ditylum*, confirming our central hypothesis for the study and providing further evidence for the importance of this heretofore scarcely studied phenomenon (**Fig. 6**). Phytoplankton composition was verified with a bench top microscope during the deployment. Horizontal, north-south orientation for the diatom chains in the layer is consistent with vertical shear occurring through the pycnocline, verified with preliminary data from the Aquadopp current profiler analyzed by postdoc Nayak (**Fig. 7**). Moreover, the suite of sensors successfully employed to document the optical characteristics, small scale physics, and natural morphological properties of naturally orienting particles in thin layers have provided us a remarkably comprehensive and sophisticated data set to evaluate the effects of this phenomenon.

The group at TAMU was able to successfully model the scattering properties of triangular prism shaped diatom chains with a spherical cell nucleus such as *Ditylum* using the many-body iterative T-matrix (MBIT) method, the invariant imbedded T-matrix (IITM) method, and an improved implementation of the ray-by-ray (RBR) geometric optics method (Sun et al., submitted). Since size ranges for the methods overlap, scattering properties for a complete range of cell sizes with this structure and shape can be effectively modeled. **Fig. 8** shows model scattering results from Sun et al. (submitted) for a chain of three *Ditylum* type cells. The shape of the VSF (labeled as P11 in the figure) is consistent with field measurements in water where the large particle subfraction was dominated by this diatom type. Surprisingly, only small deviations from 1 were observed for P22/P11, a proxy for nonsphericity, and the P12/P11, the degree of linear polarization, followed a pattern close to that expected Rayleigh scatterers, i.e., particles that are small compared with the wavelength of incident light. Results from modeling the effects of particle orientation on absorption by postdoc McFarland are shown in **Fig. 9**, with a 13-fold variability in observed absorption rate through the range of orientations for a rectangular box shape with a 20:1 aspect ratio. Results from the scattering and absorption modeling are helping us understand the dramatic effects of particle orientation on water column optical properties and light propagation, as well as the effects on light harvesting by the orienting phytoplankton chain itself.

The above results and subsequent analyses will be reported in presentations by postdocs Nayak and McFarland at the Ocean Sciences meeting in February 2016.

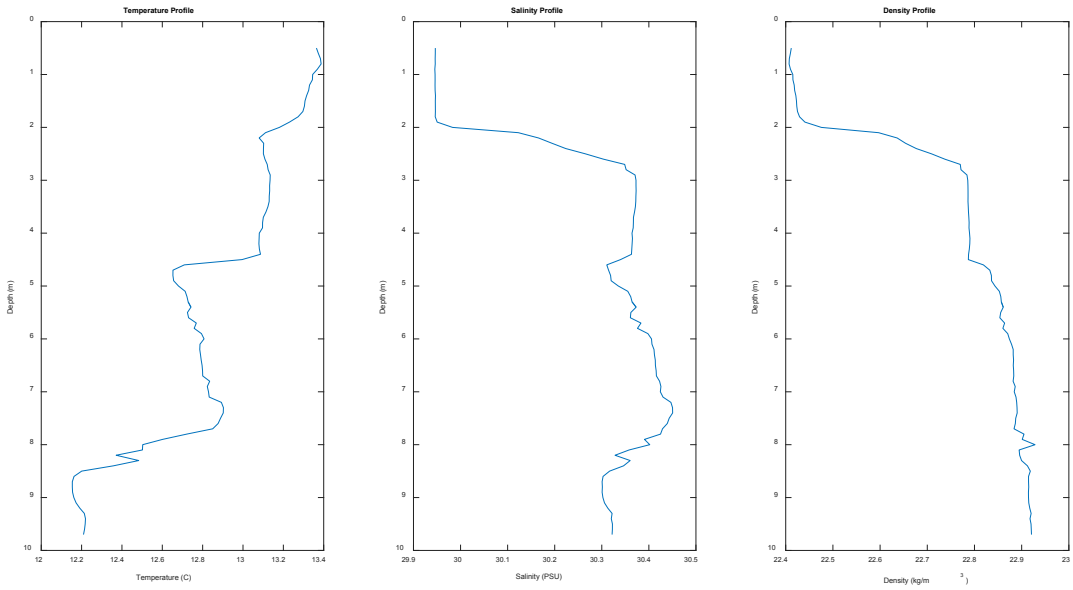

Figure 2. Temperature, salinity, and sigma-t density profiles from 9/22/15 in central East Sound. A marked pycnocline was observed between 2 and 2.8 m. Internal waves modulated this pycnocline between about 2 and 4 m during the 4 h sampling period.

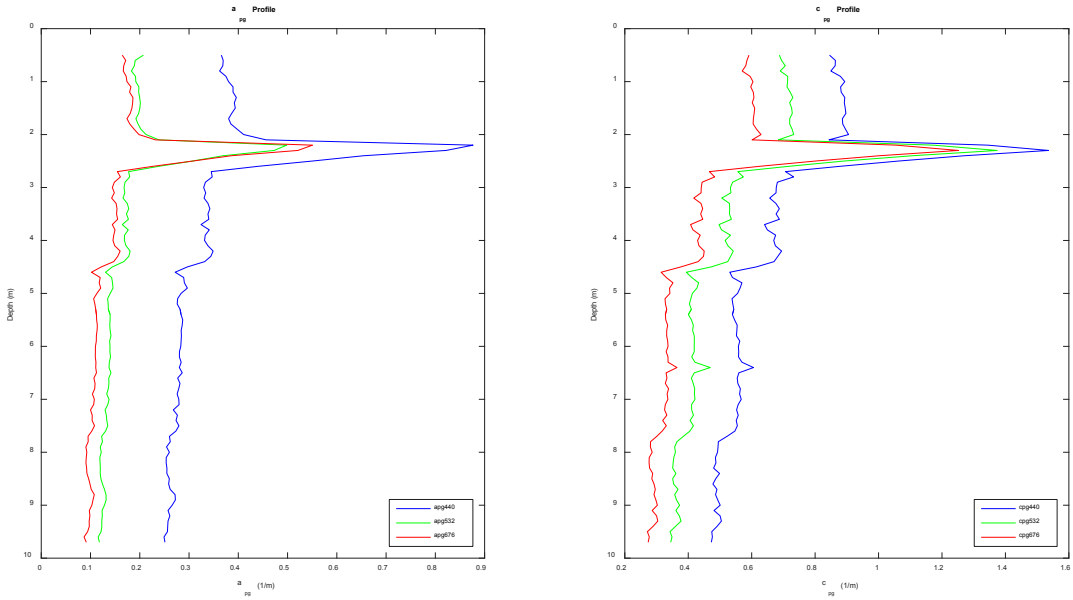

Figure 3. Profiles of spectral absorption and attenuation measured with a WET Labs ac9 at 440, 532, and 676 nm, showing an intense thin layer of particles centered at 2.2 m with FWHM width of 25 cm, occurring within the pycnocline. Peak heights in absorption and attenuation at 440 nm were 0.52 m^{-1} and 0.73 m^{-1}.

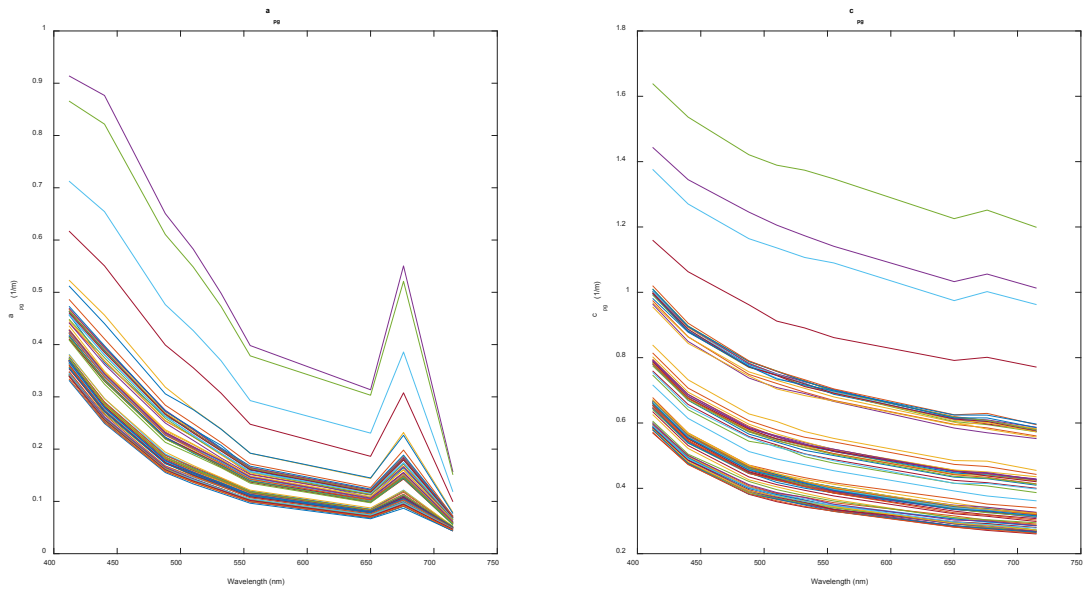

Figure 4. Spectra of absorption (left panel) and attenuation (right panel) measured through the water column with a WET Labs ac9 on 9/22/15. Highest values associated with the strong thin layer.

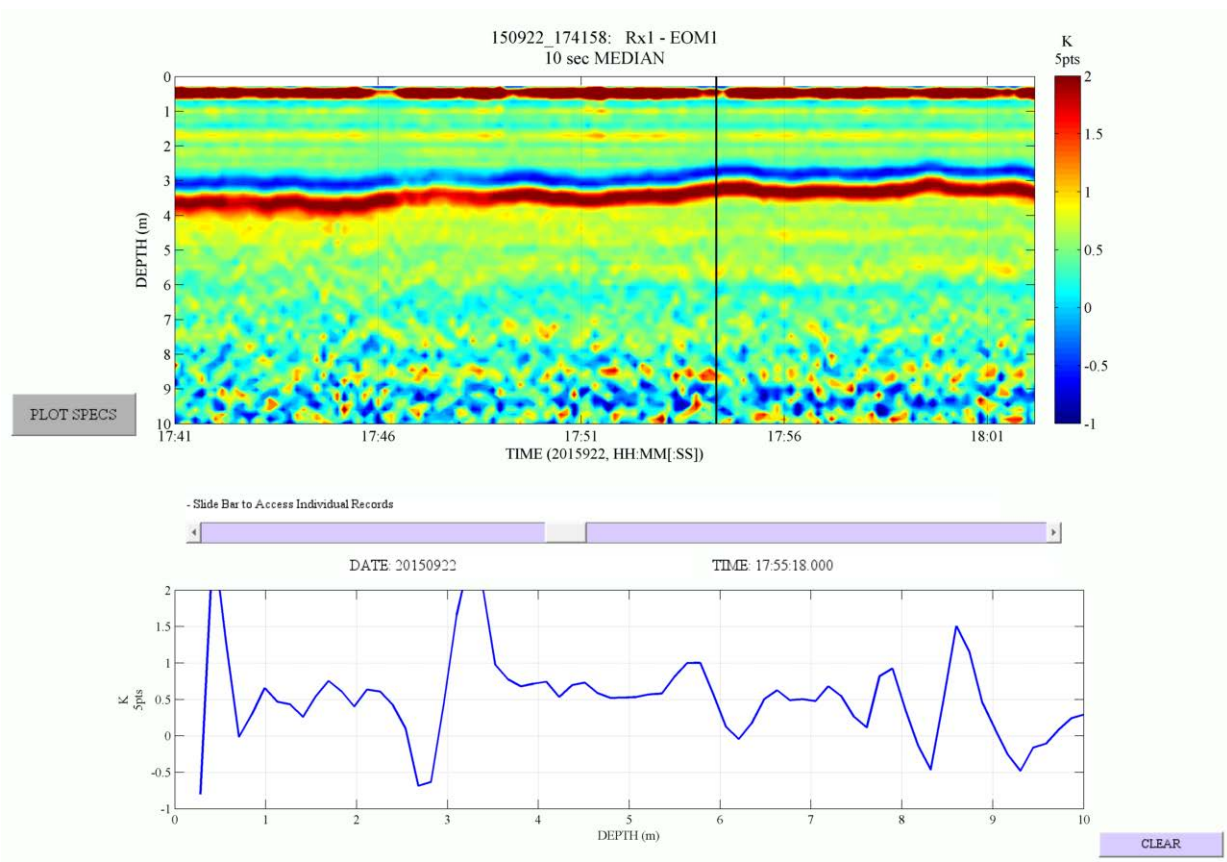

Figure 5. Time series of remotely sensed profiles of attenuation (K_{sys}) measured with the NRL above-water lidar system. An intense thin layer was observed between 3 and 4 m, corroborating observations from the suite of optical sensors on the vertical profiling package.

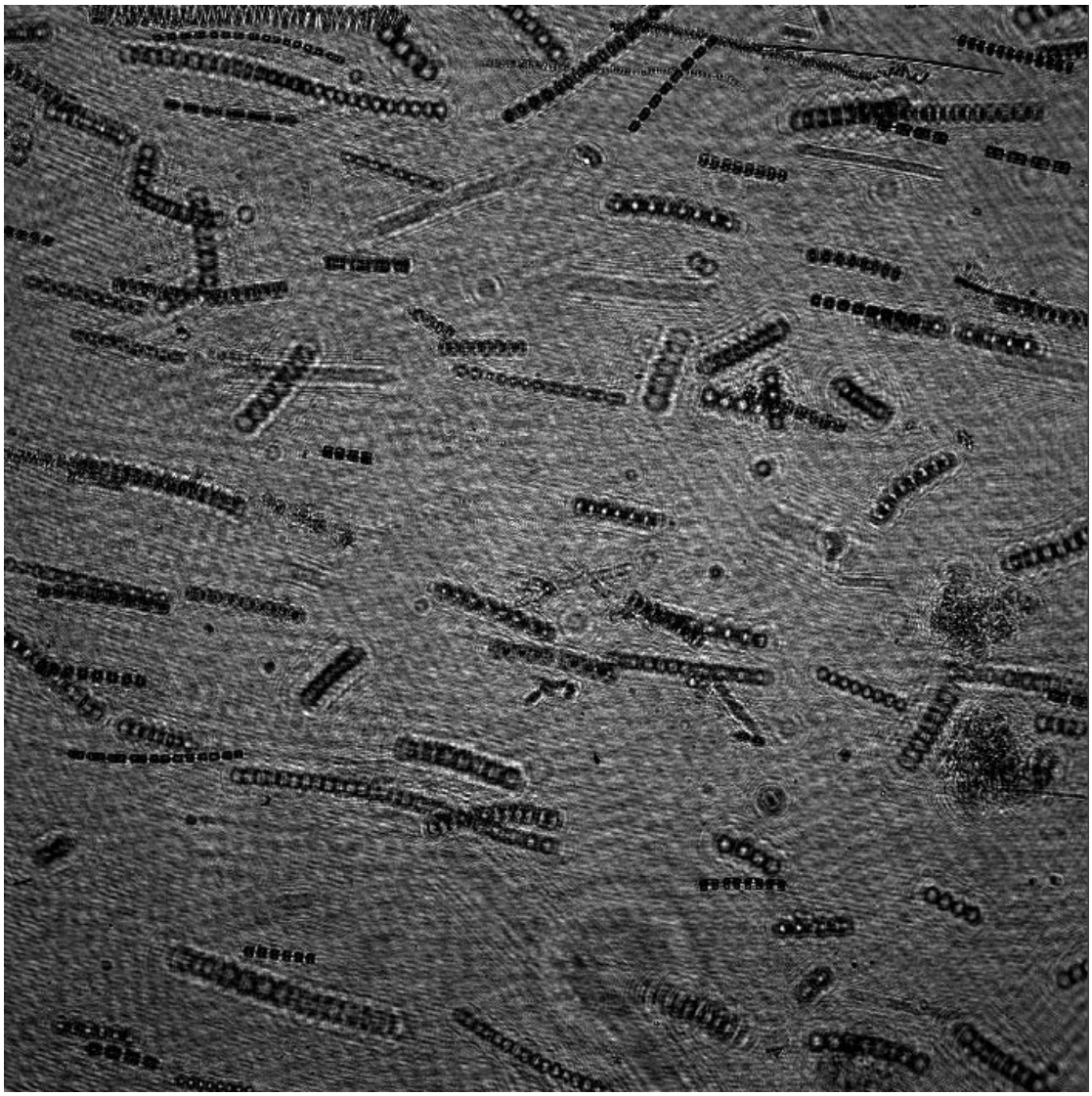

Figure 6. HOLOCAM image within the thin layer peak observed 9/22/15 showed chain-forming diatoms dominated by the species **Ditylum.** ***Most chains are several mm long, significantly longer than observed with discretely collected samples with bench top microscopy due to breakage of the chains during handling. Marked orientation of diatom chains was observed, confirming our central hypothesis for this study.***

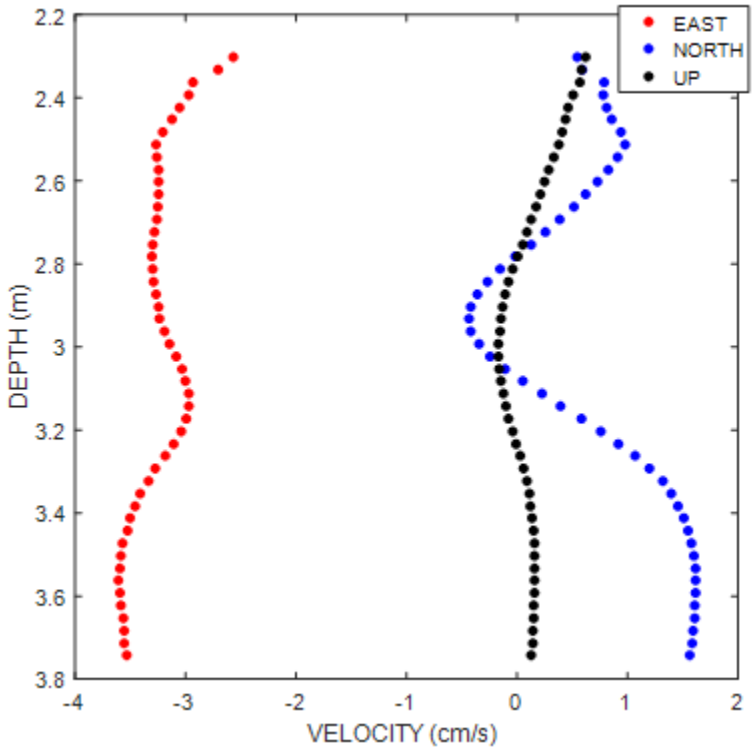

Figure 7. Current velocities measured with Nortek Aquadopp showing shear layers in the north-south velocity centered at 2.7 m and 3.1 m, consistent with observed depths of the pycnocline and thin layer.

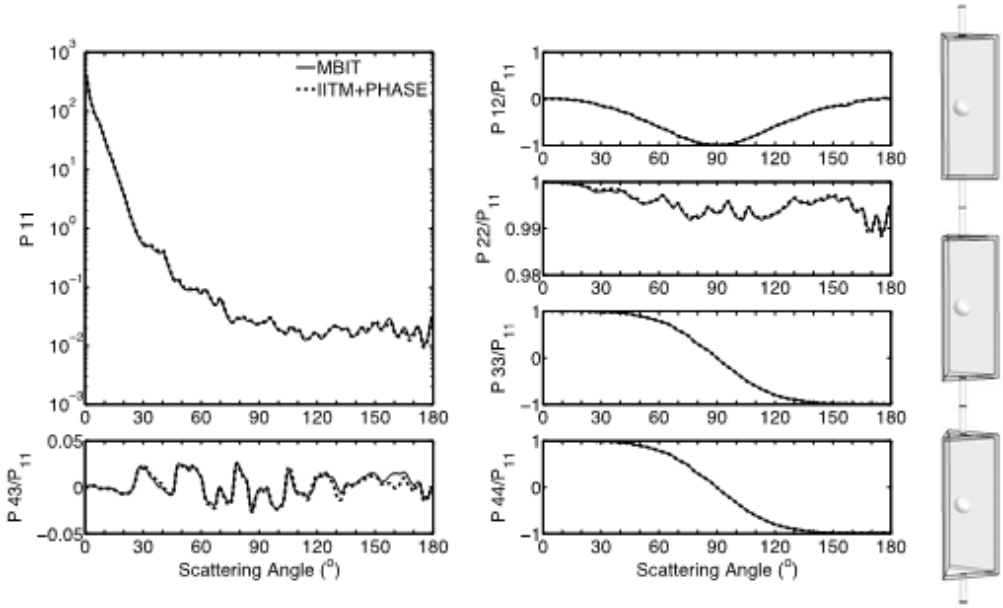

Figure 8. Modeled scattering properties using MBIT and IITM from a simulated 3-cell diatom chain, each consisting of a triangular prism with outer shell and a central nucleus core. The shape of the VSF is represented by P11, with the other parameters showing scattering by different types of polarized light. From Sun et al., submitted.

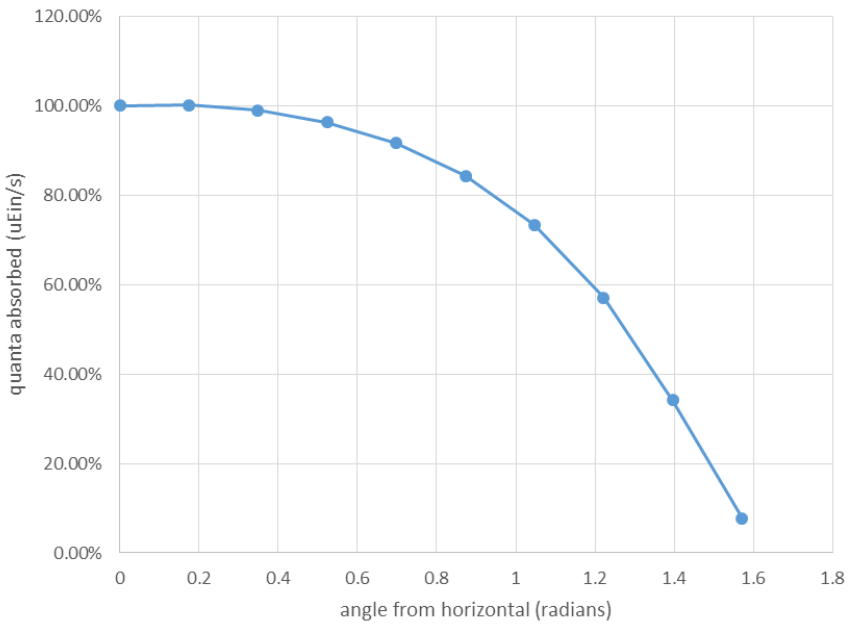

Figure 9. Model of the effects of particle orientation on absorption for a rectangular box shaped chain with a 20:1 aspect ratio. A 13-fold range of variability is observed as the particle is rotated from perpendicular (0 rad) to parallel ($\pi/2$ rad) relative to the incident light field.

IMPACT/APPLICATIONS

Knowledge of the Inherent Optical Properties (IOPs) including the VSF and any dependencies on preferentially oriented particles in the ocean can be used to predict and optimize the performance of a host of Naval operations that rely on divers, cameras, laser imaging systems, and active and passive remote sensing systems. These operations include mine countermeasures, harbor security operations, debris field mapping, anti-submarine warfare, and search and salvage operations. Our results represent the first comprehensive data set ever recorded for assessing the effects of preferential particle orientation in the ocean.

TRANSITIONS

We expect results from this work will lead to better predictive operational tools for the fleet and the oceanographic research community in the future. Commercialization of custom technologies employed for this work is also being discussed.

RELATED PROJECTS

This effort is related to the following ongoing efforts:

- "Improving retrieval of inherent optical properties from ocean color remote sensing through explicit consideration of the volume scattering function." NASA PACE Science Team (PI - Twardowski).
- "Improving inherent optical property measurement uncertainties for PACE ocean color remote sensing applications." NASA PACE Science Team (PI – Sullivan; Co-I - Twardowski).

- "TOPGATE: Performance assessment for environmental sensing system and imaging prediction algorithm." NUWC, Code 3497 Special Projects (PI – Twardowski).
- "Development and Testing of Major New Instrumentation for High Accuracy Measurement of Backscattering-bb and Total Scattering-b in Natural Waters." NSF OTIC (PI – Fry, TAMU; Co-I - Twardowski).
- "Investigating the underlying controls of biological camouflage responses in dynamic underwater optical environments." ONR MURI (PI – Cummings, UT; Co-I - Twardowski).

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HONORS/AWARDS/PRIZES

Twardowski named Program Lead for Marine Sensing and Technology Pillar subgroup at Florida Atlantic University.

Kattawar received The Oceanography Society's 2014 Jerlov Award on 10/30/2014 at the Oceanography Society's Annual Meeting in Portland, Maine.

Kattawar received 2015 van de Hulst award on 06/21/2015 at the 15th Electromagnetic and Light Scattering Conference held in Leipzig, Germany.