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Hemispherical Time-Resolved Backscatter and Attenuation Profiling of Undisturbed Particle Fields

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LONG-TERM GOALS

Our long-term goal is to develop and apply subsea LiDAR technology to better understand the fine temporal and spatial scale beam attenuation and backscatter properties of undisturbed three-dimensional scattering volumes. Such technology is important for observing intermittent turbulent mixing events and resolving short-lived processes (e.g., thermal, chemical, and biological fluxes) throughout the water column, which are otherwise nearly impossible to capture from conventional ship-based measurements. Improving measurements and prediction of energy flows in aquatic systems is very important for climate change and weather. The impact of such phenomenon on other subsea technologies such as undersea laser imaging and communications, as well as airborne LiDAR are of particular interest.

OBJECTIVES

The technical objectives of this work are focused on gathering hemispherical attenuation and backscattering profiles for randomly oriented and preferentially oriented particle layers through the water column to address the hypothesis that LiDAR-based determination of backscattering and beam attenuation profiles from multiple water column locations at multiple angles relative to the undisturbed particle field are an effective way to assess the effects of preferential particle orientation.

More specifically, if the particles are randomly oriented, then optical properties will not depend on measurement geometry, e.g., the LiDAR orientation relative to the particle field. Whereas, if the particles are preferentially oriented, the optical properties, including the cross-polarized (*crosspol)* and co-polarized (*copol)* measurements will show such dependence, and this should be reproducible and consistent with open-path inherent optical properties (IOP), holographic imaging and modeling work by collaborators Sullivan, Twardowski and Kattawar (ONR Grant N00014-15-1-2628).

The planned experiments were therefore designed to address the following hypothesis:

1. Remote, LiDAR-based determination of optical properties from multiple water column locations at multiple angles relative to the undisturbed particle field are an effective way to assess the effects of preferential particle orientation
2. If the particles are randomly oriented, then optical properties will not depend on measurement geometry, e.g., the LiDAR orientation relative to the particle field
3. If the particles are preferentially oriented, the optical properties will show such dependence, which should be reproducible and consistent with open-path IOP data, holographic imaging and modeling work by Sullivan, Twardowski and Kattawar.

APPROACH

The Ocean Visibility and Optics Laboratory at HBOI-FAU have modified an existing *in situ* multi-angle LiDAR instrument to allow attenuation and backscattering profiles to be gathered with fine angular resolution over a total solid angle of 2π steradians. These measurements were made at the same test sites in East Sound (WA) that another HBOI-FAU team led by Sullivan and Twardowski deployed their open-path IOP, vector acoustics and holographic imaging slow-drop profiler.

The multi-angle scanning LiDAR concept, which scans a grid of subnanosecond pulses, the central portion of which overlaps with the fields of view of the detector modules, has been developed and validated using side-by-side measurements from conventional *in situ* optical property devices through a wide variety of laboratory and operational environments. Recent field results (Vuorenkoski et al., 2015) demonstrate that it can correct for multiple scattering errors to retrieve accurate beam attenuation profiles through a distance consistent with analytical predictions. Our approach for this project was to reconfigure the system to allow for beam attenuation and backscattering profiles to be made at any combination of azimuthal and zenith angles over a total solid angle of 2π steradians (i.e. hemispherical).

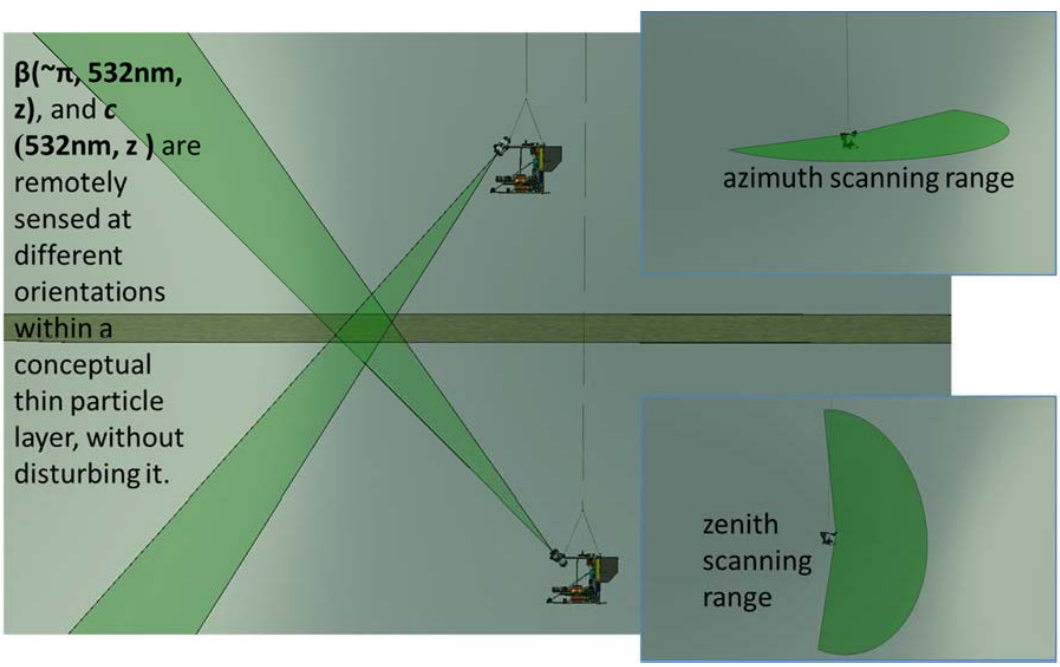

Figure 1: Graphic shows two locations where β(~π, 532nm, z), and c (532nm, z) are remotely sensed at different orientations within a conceptual thin particle layer, without disturbing it.

Consider a monochromatic angularly-dependent volume scattering function (VSF), *b(q,f,q',f')* where q and f are the zenith and azimuth angles for incident irradiance, and q' and f' are the zenith and azimuth angles for scattered radiance. At 532nm, with incident zenith and azimuth angles both ranging from 0 to 180º in any combination, with q ≈ -q' and f ≈ -f', we propose to measure depth-resolved $\boldsymbol{\beta_\pi}$ and **c**. This is shown conceptually in figure 1. With accurate knowledge of the profiler and LiDAR location and orientation, these measurements will be analyzed alongside the other open-path optical measurements.

WORK COMPLETED

The project grant was activated at HBOI-FAU on September 8th 2015. Preparations for the East Sound field experiment started during the summer and the experiment itself was held September 11th to 22nd 2015 in collaboration with HBOI-FAU colleagues Sullivan, Twardowski and NRL SSC. Internal funds were provided by the institute during the development phase, and were charged back to the project, once awarded. Photos of the hemispherical LiDAR instrument being tested on the profiler through a range of azimuthal and zenith angles during clear water tank trials are shown in figure 2.

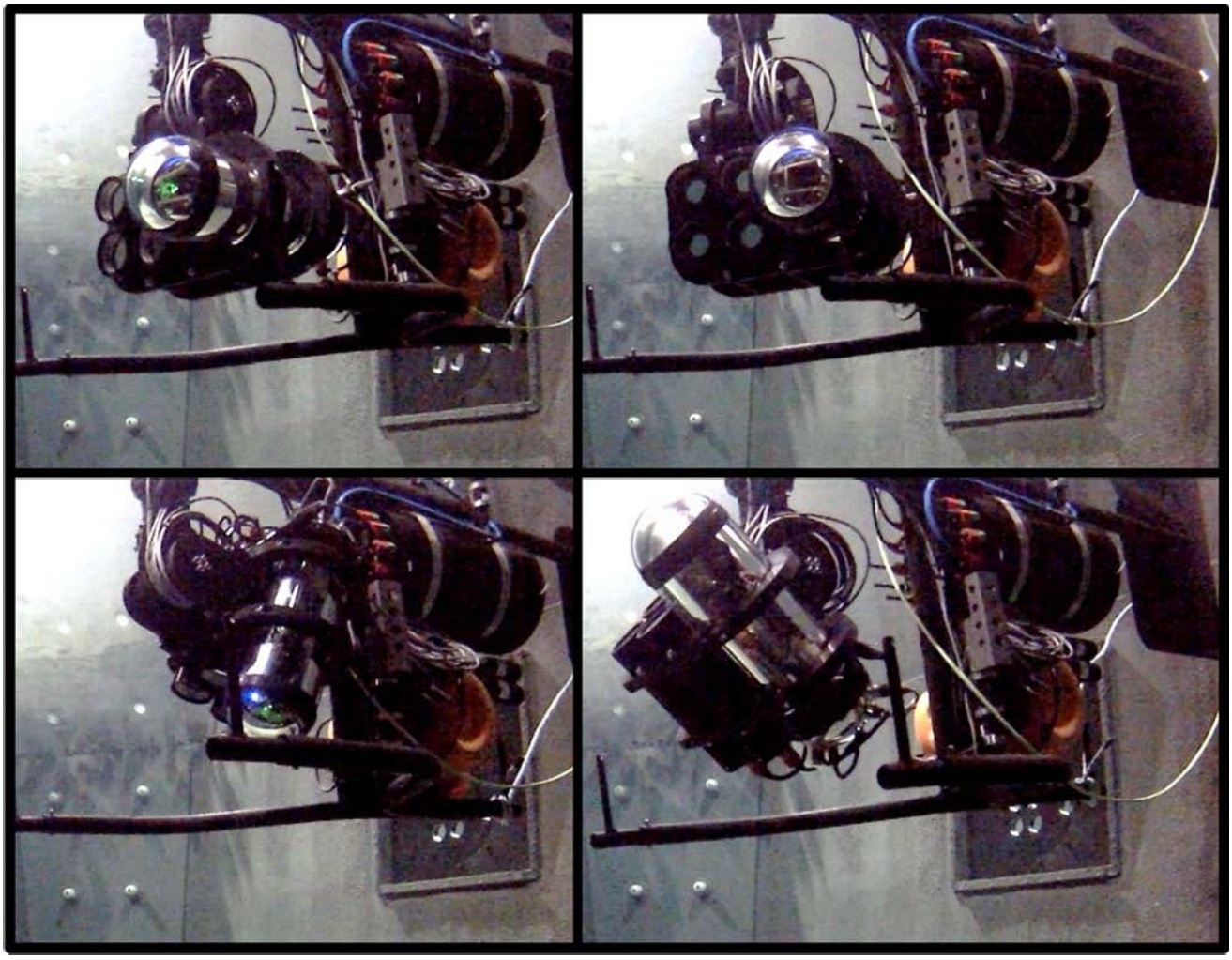

Figure 2. Tank images of the hemispherical LiDAR instrument and electronics housing being tested through a range of azimuthal and elevation angles whilst attached to the profiler prior to the deployments in East Sound, WA.

The first generation *in situ* multi-angle LiDAR has been modified to allow for beam attenuation and backscattering profiles to be made at any combination of azimuthal and zenith angles over a total solid angle of 2π steradians (i.e. hemispherical). An additional two channels have been added to provide *crosspol* and *copol* beam attenuation and backscattering profiles. Furthermore, the control and digitization functions are now performed underwater within a new electronics housing. A single power/Ethernet cable is used to trickle charge the batteries and provide a real-time interface to the instrument and viewing of the raw data being generated.

The LiDAR instrument was deployed in a series of staircase profiles above and below identified plankton layers throughout East Sound from September 11th to 22nd 2015. To characterize the water column and identify whether thin layers were present, several other optical sensing packages provided by Alan Weidemann at NRL including a shipborne LiDAR system, an imaging flow cytometer, and an above-water polarimeter, as well as the other HBOI-FAU slow drop profiling package. The HBOI group also deployed a separate package testing *in situ* absorption sensors that included the WET Labs ac9 and Turner Designs ICAM. Figure 3 shows a photo of the hemispherical LiDAR being deployed in East Sound.

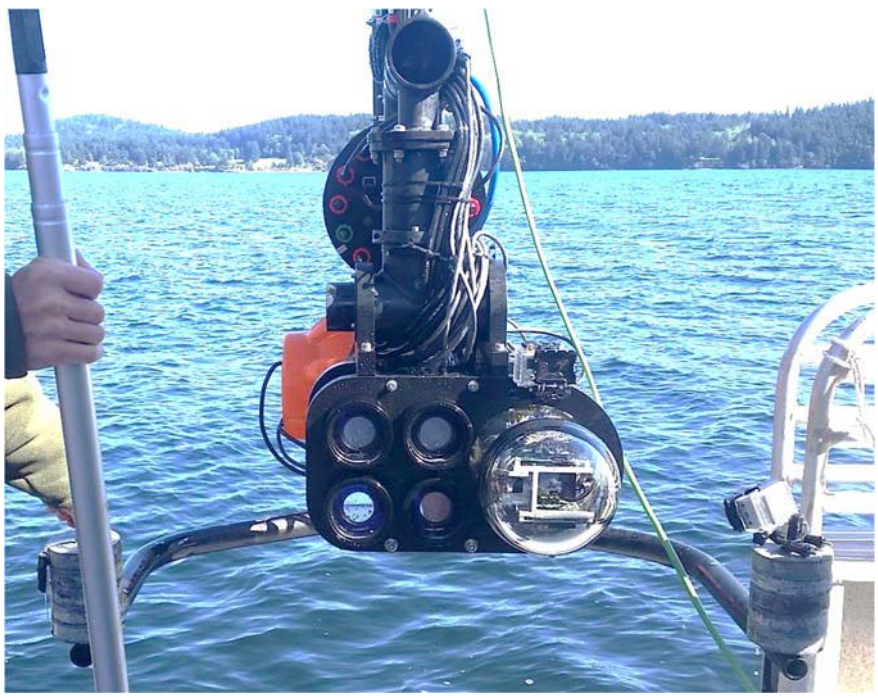

Figure 3. Front view of the ORBITAL LiDAR instrument being deployed in East Sound.

RESULTS

During the September 11th to 22nd 2015 deployment in East Sound, data was gathered on seven days with the hemispherical LiDAR instrument. The LiDAR dataset, which is known to be partially corrupted in the sense that not all pulse positions were successfully triggering the acquisition of waveforms, due to a buffer overflow issue with the new digitizer which wasn't resolved until after the cruise, has not been processed or analyzed in detail yet. However, a sample of raw data is shown in figure 4, which shows the 4 instantaneous LiDAR waveforms generated from a single pulse whilst the

instrument is looking upward (azimuth = 0, zenith = +90 degrees) from 7 m water depth. The return from the single layer at approximately 3.5 m water depth is seen together with the near-surface return from the bottom of the research vessel. A video frame from monitoring GoPro™ camera attached to the LiDAR is also shown for reference. This raw data was taken from a thin layer observed on September 22nd 2015, with a 25 cm full-width-half-max intensity in attenuation, oscillating with internal waves between 2 to 4 m in depth. More information about the optical properties of this layer is described in the Twardowski and Sullivan annual report.

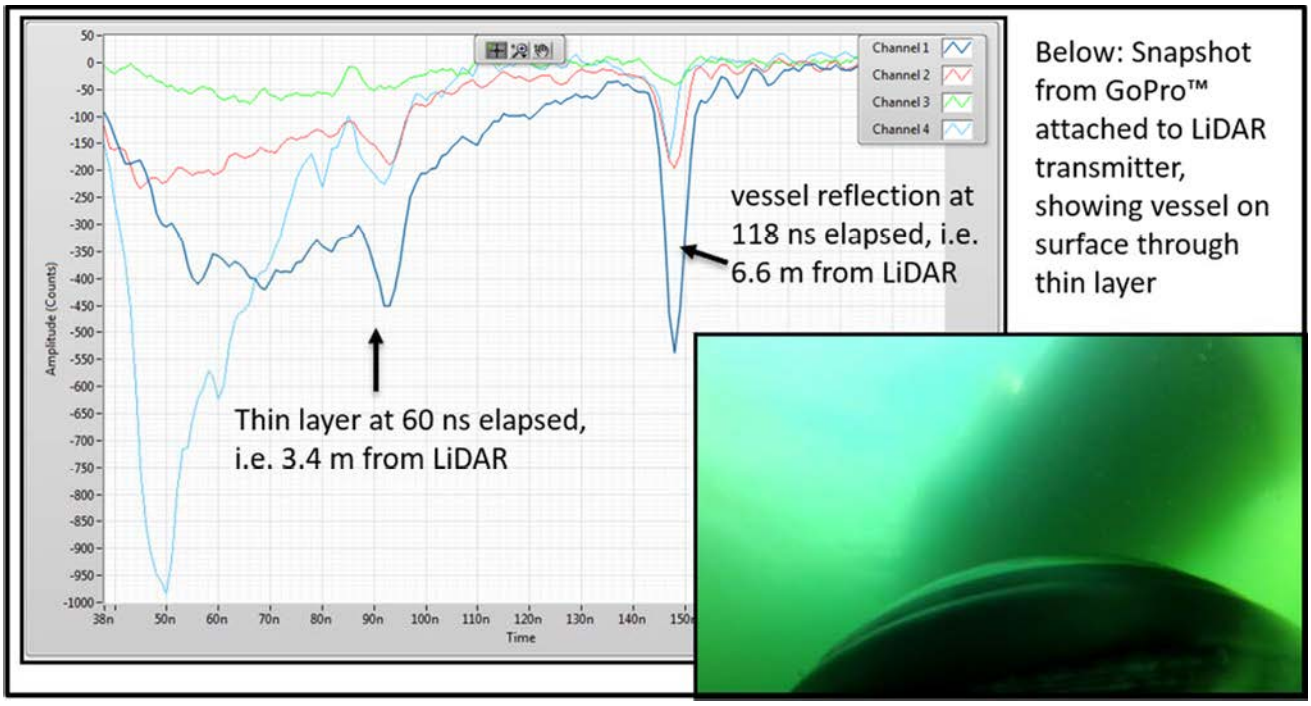

Figure 4. Sample raw waveforms from a single pulse position, while LiDAR is held at azimuth = 0 degrees, zenith = +90 degrees. Inset photo from monitoring GoPro™ camera shows the LiDAR transmitter (below) and the deployment vessel hull (above).

IMPACT/APPLICATIONS

The outcome of this project could be important in interpreting and understanding bias in signals from both operational and developmental optical remote sensing systems and algorithms. Furthermore, the potential of subsea LiDAR technology for real-time data resolving of optical properties and aspects of particle and turbulent layers could provide critical data for many of the operational ecosystem monitoring, ocean modeling, and forecasting efforts of the Navy, providing improved synopticity and persistence of observations, and enabling operational applications in the areas of MCM, ISR and ASW.

TRANSITIONS

More results will be collected in the November 2015 Alboran Sea cruise, Alomex ’15, led by CMRE.

RELATED PROJECTS

This effort is related to the following ongoing efforts:

- "Unobtrusive Multi-static Serial LiDAR for Surveillance and Identification of Marine Life at Marine Hydrokinetic Installations" US Department of Energy (Energy Efficiency and Renewable Energy (PI - Dalgleish, co-I - Vuorenkoski-Dalgleish, co-I - Ouyang).
- "Advanced Glider Sensing Technologies for Innovative Studies at Coral Reef Ecosystems" NOAA OAR (PI - Vuorenkoski-Dalgleish, co-I - Dalgleish, co-I - Ouyang, co-I - Cherubin)
- "Expanding applicability of the compressive line sensing underwater laser imaging system" ONR (PI – Ouyang, co-I - Vuorenkoski-Dalgleish, co-I - Dalgleish, co-I - Wang)
- "Airborne Compressive Sensing Topographic LIDAR" AFOSR (PI – Ouyang, co-I - Vuorenkoski-Dalgleish, co-I - Dalgleish)

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Vuorenkoski, A.K., Dalgleish, F.R., Twardowski, M.S., Ouyang, B., and Trees. C. C. (2015) Semi-empirical inversion technique for retrieval of quantitative attenuation profiles with underwater scanning LIDAR systems. Proc. SPIE 9459, Ocean Sensing and Monitoring VII, 945915 (May 19, 2015).

PUBLICATIONS

Dalgleish, F. R., Shirron, J. J., Rashkin, D., Giddings, T. E., Vuorenkoski, A. K., Cardei, I., Ouyang, B., Caimi, F. M. and Cardei, M. 2014. A Physical Layer Simulator for Undersea Free Space Laser Communications*, Optical Engineering,* 53 (5): 051410 (April 25, 2014); doi: 10.1117/1.OE.53.5.051410 PUBLISHED

Ouyang, B., Dalgleish, F. R., Caimi, F. M., Giddings, T. E., Britton, W. B., Vuorenkoski, A. K, and Nootz, G. A. 2014. *Compressive line sensing underwater imaging system*. *Optical Engineering,* 53 (5): 051409 (April 22, 2014); doi: 10.1117/1.OE.53.5.051409 PUBLISHED

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Ouyang, B., Hou, W., Caimi, F. M., Dalgleish, F. R., Vuorenkoski, A. K., Gong, C., and Britton, W. B. (2015). Near-Infrared Compressive Line Sensing Imaging System Using Individually Addressable Laser Diode Array. Proc. SPIE 9484, Compressive Sensing IV, 948401 (May 14, 2015).

HONORS/AWARDS/PRIZES

Dalgleish received the 2015 Researcher of the Year award (Associate Level) at Florida Atlantic University.