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Remote sensing of optical characteristics and particle distributions of the upper ocean using shipboard lidar

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ABSTRACT

Passive ocean color remote sensing has revolutionized our ability to quantify the horizontal distribution of phytoplankton across the ocean surface. Lidar technology can provide remotely sensed estimates of the vertical distribution of optical properties and suspended particles in natural waters, significantly improving our ability to model upper ocean biogeochemical processes. In this study, we constructed and deployed a ship-based lidar system to measure laser backscattering and linear depolarization profiles in the coastal Mid-Atlantic ranging from estuarine to oceanic conditions, and across the Gulf of Maine (GoM). The instrument identified layers with different backscattering intensity in stratified waters of the coastal Mid-Atlantic and produced system attenuation coefficients (K_{sys}) approximating the absorption coefficient (a_{pg}) of particulate + dissolved matter. The linear depolarization ratio was strongly related to in situ measurements of the particulate backscattering ratio (b_{bp}/b_p). Measurements of K_{sys} and linear depolarization made across the GoM corresponded well with simultaneous in situ observations performed aboard the M/V Nova Star and by an autonomous glider deployed along the transect. The relationship between K_{sys} and a_{pg} differed between sampling schemes, likely due to differences in the deployment geometries (e.g., height, nadir angle). These results support the proposition that ship-based lidar systems can provide a powerful tool for remotely measuring the vertical distributions of optical properties and geochemical constituents (e.g., particles) in the upper ocean. Continued development of compact lidar systems for deployment on ships, moorings, and autonomous platforms has the potential to greatly improve the quality and scope of a variety of oceanographic investigations.

1. Introduction

The use of lidar in the geosciences has grown tremendously in recent years with the advent of extremely fast electronics, laser miniaturization technology, high-speed/high capacity computers, and satellite-based global navigation systems (Kovalev and Eichinger, 2004). Practical lidar systems for mapping underwater topography and bathymetry were first developed in 1994 (Lilycrop et al., 1996), and are now widely used for government, industrial, and commercial applications (Mallet and Bretar, 2009). The first commercially available systems were designed for topographic mapping, and provided only a single backscattered echo per pulse. Later, multi-echo systems were employed for the discrimination of buildings, vegetation canopy structure, and other non-topographic features. Dramatic advances in high-speed electronics and data storage capacity now enable development of full waveform lidar systems that record the backscattered laser energy as a continuous function of time, remotely revealing the internal structure of the ocean, at least on an experimental basis (Churnside and Wilson, 2001; Hill et al., 2013; Lee et al., 2013).

The potential for oceanographic lidar to map the vertical distribution of subsurface oceanic scattering layers was first demonstrated using the NASA Airborne Oceanographic Lidar (AOL). Working in coastal waters of the Mid-Atlantic Bight, Hoge et al. (1988) found low lidar backscattering with very little vertical structure in the clear waters of the Sargasso Sea (~36° N, 72.5° W), increased scattering in the upper 15 m of the water column along the shelf-slope transition (37.5° N, 74° W), and very high scattering with clearly defined subsurface turbidity layers in shelf waters near Wallops Island, Virginia (37.8° N, 75.2° W). The observed scattering signals were attributed to phytoplankton in the offshore waters and a combination of plankton and suspended sediments on the shelf, but the study lacked sufficient in situ measurements to directly link the lidar signals with optical and/or material properties

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of the water column. Subsequent work in the Southern California Bight (Churnside et al., 1998) and Key West, Florida (Allocca et al., 2002) demonstrated quantitative, albeit imperfect, relationships between the lidar system attenuation coefficient (K_{sys}) and beam attenuation coefficient that could provide utility for remotely mapping the vertical distribution of biogeochemically relevant particles in the upper ocean. More recently, airborne oceanographic lidar has been used to map a variety of upper ocean properties, including fish schools and thin scattering layers (1 to 3 m thick) generated by phytoplankton, and relate their distributions to a number of important oceanographic processes, including primary production, internal wave propagation, wind-driven and topographic upwelling, and eddies (Churnside and Donaghay, 2009; Churnside and McGillivary, 1991; Churnside and Wilson, 2001; Churnside et al., 1997; Lee et al., 2013; Schulien et al., 2017).

The above studies have provided tantalizing examples of the potential for oceanographic lidar to remotely map the vertical structure of the upper ocean and identify important features (sediment plumes, thin layers, fish aggregations, etc.), but this technology remains experimental and has yet to transform our understanding of the vertical dynamics of the upper ocean, and its interaction with the overlying atmosphere in ways comparable to passive ocean color remote sensing (OCRS) (Martin, 2004). Despite its transformative contribution to ocean science, the utility of OCRS data is limited by its inherent reliance on a passive source of visible light, the sun. Consequently, OCRS data acquisition is limited to well-lit, cloud-free scenes, leaving polar regions, which experience persistent cloud cover and low solar zenith angles, poorly documented. The active, range-resolved nature of the lidar return signal may permit greater remote coverage of these regions regardless of available sunlight and in the presence of some cloud cover (Behrenfeld et al., 2017).

Furthermore, the remotely sensed spectral radiance emanating from the ocean surface represents an integrated signal limited to the upper portion of the euphotic zone (~2 optical depths), that provides no information on the vertical distribution of optically important materials deeper within the water column, and potentially misses significant populations of primary producers growing throughout the lower portion of the euphotic zone. The lack of information regarding the vertical distribution of relevant material and optical properties, including concentrations of phytoplankton (measured as chlorophyll *a* concentration [Chl]), chromophoric dissolved organic matter (CDOM), suspended sediment or detritus, and diffuse attenuation [e.g., $K_d(490)$] can lead to significant errors in the interpretation of the oceanographic processes involving these components (Hill et al., 2013; Hill and Zimmerman, 2010; Lee et al., 2015; Schulien et al., 2017). Vertically resolved estimates of these properties from lidar offer to fill this gap in our remote sensing capabilities, improving estimates of not only the standing stock concentration of these properties, but also the rate processes in which they are involved (Hill and Zimmerman, 2010; Schulien et al., 2017).

In addition to information on depth-resolved backscattering intensity and attenuation, lidar can provide information about the material composition of distant targets by measuring the extent of depolarization in the backscattered signal. Depolarization of the lidar signal is sensitive to a variety of material properties of the sampling volume, including particle shape, size, and bulk refractive index (Hu et al., 2001; Sassen, 1991, 2005), which may permit oceanographic lidar to quantify a variety of particles including phytoplankton, organic and inorganic detritus, suspended sediments, and even fish (Churnside, 2008; Hoge, 2006; Tenningen et al., 2006).

Optical properties represent excellent proxies for various ocean biogeochemical parameters, a fundamental tenet for all optically based oceanographic sensors (Twardowski et al., 2005). The pioneering studies cited above revealed the capability of oceanographic lidar to remotely map the vertical distribution of important features in the upper water column as a semi-quantitative product of lidar scattering and/or attenuation, but could not always relate lidar signals to in situ measurements of optical properties. The next important step in the development of this technology for oceanographic applications involves rigorously quantifying the vertical distribution of optical properties (*a*, *c*, K_d), and, by proxy, biogeochemical quantities (e.g., phytoplankton, suspended sediment and detritus) from the lidar signals. The purpose of this study was to (i) develop a portable ship-based lidar system, (ii) characterize its return signal, and (iii) explore its utility in remotely characterizing the spatial structure of optical and biogeochemical properties of the water column from stationary and moving vessels.

2. Methods

2.1. Instrument design

Our lidar system utilized a Litron Q-switch pulsed Nd:YAG laser (1064 nm), frequency doubled to 532 nm, emitting a 20 mJ pulse of linearly polarized light with a full angle beam divergence of < 2 mrad, and a full-width half-max (FWHM) pulse width of 4 ns. The emitted pulse was directed through a beam expander telescope and a pair of laser line mirrors (Thorlabs Model NB1-K13) that oriented the beam parallel to the viewing geometry. After exiting the beam steering assembly, the emitted pulse had a spot diameter of 1 cm, and a full angle divergence of < 0.5 mrad. The laser pulse exited through an acrylic window in the bottom of a watertight anodized aluminum housing, allowing the lidar to be deployed either below the water surface or above water from a floating or moving platform (Fig. 1). The return pulse travelled through a 532 nm narrow-band interference filter positioned at the front-end of the collection optics assembly (Semrock LL01-532-12.5; 2.0 nm FWHM bandwidth; 12.5 mm diameter) to exclude background light. An anti-reflection coated polarizing beam splitter cube (CVI PBS-532-050; 1000:1 T_p/T_s extinction ratio; $T_p > 95\%$, $R_s > 99.9\%$) was used to separate the co-polarized and cross-polarized signals that were directed onto fast (< 1 ns pulse width, narrow spread in transit time) photomultiplier tubes (PMTs, Hamamatsu Model H10721–20). No additional collection optics (lenses or mirrors) were used in the system receiver. Stray capacitance in the detector signal circuitry broadened the apparent instrument pulse width to 7 ns. For these deployments, the system field of view (FOV) was constrained by the acceptance angle of the interference filter to be 14° (full angle). The detector axis was oriented biaxial to the laser source with a 3.5 cm offset. According to this geometry, the range to complete overlap between the detector field of view and the laser source occurred at 29 cm when deployed above water, and 38 cm when deployed below the sea surface. This distance is sufficiently short that we opted to exclude data within this region from the analysis rather than to correct it for the overlap function given that the overlap function exhibits complex dependencies on a variety of instrument and water column properties.

The co-polarized and cross-polarized return signals were recorded digitally at a sampling rate of 1 GSamples s^{-1} channel^{-1} with 8-bit resolution using a National Instruments (NI) PXI-5154 digitizer in conjunction with an NI data acquisition module (PXI-5154) and chassis (PXI-1042) operating under Microsoft Windows. Aspects of the lasing system (laser power and repetition rate) were controlled using Litron's proprietary laser control system (Litron Laser Control Client). The detector and data acquisition systems were controlled using custom software written in *LabView*® that allowed for adjustment of sample frequency and PMT gain via a graphical user interface. For a synopsis of the instrument characteristics, the reader should refer to Table 1.

2.2. Mid–Atlantic in-water deployments

The lidar was initially field tested during two day-cruises (May 4, 2015 and June 30, 2015) into the Mid-Atlantic Bight aboard the *R/V Fay Slover*. These cruises were characterized by strong horizontal gradients in optical properties ranging from clear oceanic water at the offshore region to highly turbid estuarine water close to the mouth of