Oceanic inherent optical properties: proposed single laser lidar and retrieval theory

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It is suggested that an economical airborne lidar having a single laser can retrieve the three principal inherent optical properties of the ocean. Only three time-resolved backscattering receiver channels are required: (i) elastic (on-wavelength), (ii) inelastic (water Raman), and (iii) inelastic [chromophoric dissolved organic matter (CDOM) fluorescence channel to remove the CDOM fluorescence interference from the Raman channel].

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1. Introduction

Recently, it was shown that a dual-laser lidar could be used to retrieve three principal inherent optical properties (IOPs) of the ocean (a_{ph}, a_{CDOM}, and b_{bt}, respectively, the phytoplankton absorption coefficient, chromophoric dissolved organic matter absorption coefficient, and total backscattering) using time-resolved elastic backscattering from two receiver channels.[1] Recent radiative transfer modeling results (as validated with Monte Carlo simulations) suggest that inelastic (e.g., water Raman) backscattering signal returns have the same basis[2] as the elastic backscattering.[3] These findings form the hypothesis of this paper: that only one laser is required (that concurrently produces both the elastic and the inelastic backscattering returns). Thus it is the objective of this paper to (i) call attention to new lidar modeling results and (ii) suggest application of the results to the development of economical and less complex airborne lidar systems.

A strong motivation for an airborne single-laser lidar system is to provide municipalities, state governments, and less developed countries the opportunity to develop a lightweight, small-volume, low-power consumption, airborne lidar system that is not only effective in water quality investigations but economical to assemble, operate, maintain, and upgrade as new technology becomes available. These attributes are consistent with the model for lidar system development that has been realized by progressive improvements of the NASA Airborne Oceanographic Lidar (AOL).[4] It is notable that the original AOL in 1977 required forklifts for lifting and installation aboard four-engine C-54 and/or P 3-A aircrafts. Today, the third-generation AOL can be installed aboard a two-engine Twin Otter-type aircraft by two technicians.[4]

2. Single-Laser Lidar System Considerations

A single-laser lidar system can be easily configured to have a receiver band at the usual elastic channel and accompanying inelastic water Raman and CDOM fluorescence channels. For example, the 1064 nm Nd:YAG laser frequency tripled to 355 nm has been used for many years in airborne applications.[5–7] (For the 355 nm wavelength, the ~3250 cm^{-1} OH-stretch water Raman scatter occurs at ~402 nm and the peak CDOM fluorescence at ~450 nm.) The 355 nm laser is a strong candidate laser since (i) it incurs considerable CDOM absorption in the UV and (ii) it concurrently undergoes modest phytoplankton absorption there and at 402 nm.[8] The system discussion herein assumes a 355 nm laser lidar.

(The frequency-doubled Nd:YAG at 532 nm is considered acceptable but not optimal for retrieval of the three principal oceanic IOPs. For example, sparse CDOM absorption occurs at both 532 nm and at the Raman wavelength of ~645 nm so its sensitivity to the retrieval of CDOM absorption is likely compromised. Also, the phytoplankton absorption maximum is in the range of ~430–450 nm and is therefore not well matched to the 532 nm wavelength or its ~645 nm Raman.)

Tunable optical parametric oscillators (OPO) or op-

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tical parametric amplifiers (OPA) appear to be even better candidates since the emission wavelength can be chosen to accommodate the broad UV–visible CDOM absorption and narrower visible absorption phytoplankton bands.

Since $k_{elastic}$ (this in-water, altitude and water-depth corrected attenuation coefficient is defined later) at null depth will be required, then a narrow transmit pulse width, ~1 ns,[9,10] is suggested for good depth resolution. It follows that a wide bandwidth receiver is also required. The narrow pulse will enable better separation of the strong Fresnel surface reflection from the desired null depth return component.[1]

While the relationship $k_{\text{elastic}} \Rightarrow$ *total absorption*, a is used in the limit of vanishing depth, Fig. 3 in Walker and McLean[9] shows that the retrieval of a will be highly variable for narrow fields of view (FOVs) (~1 mrad) in the null depth limit. The reason for this is the large slope of k_{elastic} versus depth. For a baseline wide FOV (100 mrad),[1,9] the slope of the k_{elastic} versus depth graph is much smaller, suggesting that a reasonable estimate of a could be obtained at a depth of ~1–2 m. Further, their data also indicate that extrapolation to null depth from depths >2 m may also be possible for a wide FOV. For these reasons a wide FOV lidar system is hereby recommended. Other lidar receiver considerations are outlined elsewhere for elastic lidar retrieval of IOPs.[1]

It should be pointed out that one advantage intrinsic to the inelastic channels is its lower return signal variability than is found in the elastic channel. This lower variability is largely attributable to the single traversal of the water-to-atmosphere interface at the inelastic wavelength. Additional details including multiple FOV receiver configurations can be found in a previous publication.[1]

A high-resolution time digitizer is an important component of the data acquisition system to accurately define the sensing depth. High-resolution off-the-shelf or commercially available time digitizers are sufficient for implementation of the methods described herein.[1]

3. Theory

The theory for a single laser lidar having an elastic and an inelastic Raman band closely parallels the two-color laser elastic-only lidar system[1] but, of course, differs in the use of the inelastic backscattering. At the risk of being redundant with prior similar descriptions,[1] the retrieval is summarized here for the reader's convenience. Using a Monte Carlo validated beam spread function model,[10] it has been shown[9] (e.g., see Figs. 3 and 4 in Ref. 9) that, irrespective of the FOV, the elastic lidar attenuation coefficient $k_{\text{elastic}} \Rightarrow a$, the total absorption coefficient, as the lidar range $\zeta \Rightarrow 0$. The parameter k_{elastic} is the negative slope of $\frac{1}{2} \ln [P(\zeta)/P(\zeta_{\text{reference}})]$ versus ζ, where $P(\zeta)$ is the received lidar signal from range ζ and $\zeta_{\text{reference}}$ is a shallower reference range near the air–water interface. Similarly, for the inelastic channel, $k_{\text{Raman}} \Rightarrow a$. This latter inelastic supposition is based on recent Monte Carlo validated radiative transfer results for lidar elastic backscattering[3] as extended to lidar inelastic backscattering.[2] (Note: the CDOM fluorescence interference must be removed from the Raman band before k_{Raman} is used within the algorithm. Laboratory and airborne studies suggest that ~0.59 of the CDOM fluorescence present at 450 nm must be removed and/or subtracted from the Raman band[11,12] before k_{Raman} can be used within the retrieval algorithm; i.e., the Raman signal is equal to the total radiance at ~402 nm–0.59 of the CDOM signal at 450 nm. Note further that the theory herein is valid for a homogeneous ocean, but deviations from homogeneity are easily identified in the temporal backscattering data and removed prior to final processing.)

4. Summary and Discussion

In a previous paper it was shown that dual-laser lidars can yield two total absorption values (one from each elastic receiver channel) that can be solved by linear methods to provide the main oceanic absorption coefficients: phytoplankton absorption coefficient, a_{ph}, and chromophoric dissolved organic matter absorption coefficient, a_{CDOM}. Herein it is suggested that a single laser lidar can be used to retrieve the same optical properties by utilizing the usual elastic channel together with an inelastic water Raman channel (whose CDOM fluorescence interference has been removed). The radiative transfer-based retrieval of the optical properties is summarized for the case of one inelastic and one elastic receiver channel.

A single laser lidar would be less complex, occupy less volume, and require less power than dual-laser lidar systems. The lighter weight of a single laser lidar would potentially allow it to be flown on smaller and less expensive aircraft. With increasing federal mandates, this could encourage municipalities, state governments, and nonprofit organizations to address water quality studies that were formerly not economically feasible.

As with dual-laser lidar system hardware implementation, a narrow FOV configuration is also not recommended because of the high uncertainty in k_{elastic} and k_{Raman} as null depth is approached. The more desirable wide FOV configuration can be applied during nighttime operations but probably requires multiple FOV segments to limit daytime background noise. Multiple FOV lidar configurations[15–18] are more common in atmospheric research but should be considered for the oceanographic application described herein. No significant technological advances are required to implement the single laser lidar suggested herein, and thus existing off-the-shelf or commercially available lasers, telescopes, and time digitizers are generally suitable.