# Validation of satellite-retrieved oceanic inherent optical properties: proposed two-color elastic backscatter lidar and retrieval theory

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Recent radiative transfer models show that: (1) regardless of elastic lidar receiver field of view (FOV), at vanishing lidar depth the lidar-derived attenuation coefficient $k_{\mathrm{lidar}} \rightarrow a$, where $a$ is the total absorption coefficient per meter of depth; and (2) for a wide FOV as the lidar sensing depth approaches some large value (depending on water type), $k_{\mathrm{lidar}} \rightarrow K_d$, where $K_d$ is the diffuse attenuation for downwelling irradiance. As a result, it is shown that a time-resolved, dual-wavelength-laser, elastic-backscattering lidar can retrieve the three principal oceanic optical properties: (1) the absorption coefficient of phytoplankton $a_{\mathrm{ph}}$, (2) the absorption coefficient of chromophoric dissolved organic matter (CDOM) $a_{\mathrm{CDOM}}$, and (3) the nonwater total constituent backscattering coefficient $b_{\mathrm{bt}}$. The lidar-retrieved $a_{\mathrm{ph}}$, $a_{\mathrm{CDOM}}$, and $b_{\mathrm{bt}}$ inherent optical properties can be used to validate corresponding satellite-derived products such as those from terra moderate-resolution imaging spectroradiometer (MODIS), Aqua MODIS, Sea-viewing Wide Field-of-view Sensor, (SeaWiFS), and other ocean color sensors. © 2003 Optical Society of America

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## 1. Introduction

Terra MODIS (moderate-resolution imaging spectroradiometer), Aqua MODIS, and Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) satellite-derived water-leaving reflectances allow the retrieval of absorption coefficients of phytoplankton $a_{\mathrm{ph}}$ and chromophoric dissolved organic matter (CDOM) $a_{\mathrm{CDOM}}$. The retrieval algorithms for these satellite inherent optical properties (IOPs) are routinely developed and validated with a robust airborne lidar fluorosensor.[1–4] However, there are several plausible reasons to suggest the development of a dual-laser elastic lidar. First, for those laboratories having limited resources, an elastic lidar can potentially provide a more economical alternative to a fluorescence lidar, i.e., only two elastic receiver channels are required to retrieve the three principal IOPs (and this can be further reduced to only one channel if a fiber-optic delay segment can be implemented from channel 2 of the spectrometer into the channel 1 photodetector). Second, the elastic radiative transfer physics is more fully developed (in contrast to the present redshifted empirical phytoplankton and CDOM absorption surrogates composed of inelastic fluorescence/Raman ratios). Better modeling and understanding of the elastic lidar returns leads to a better understanding of the fluorescence and Raman emissions as well. Third, a rather wide range of elastic transmit wavelengths can be used for the IOP retrievals (while, if desired, concurrently allowing for more optimum excitation of taxanomically important phytoplankton fluorescence and spectral placement of the water Raman emissions). Fourth, presently, the backscattering coefficient is not obtainable from fluorescence or Raman emissions but would be available from an elastic lidar configuration.

Thus the objective of this paper is to propose a dual-laser elastic-backscattering lidar configuration and theory for (1) retrieval of the total absorption coefficient $a$ (and the resulting $a_{\mathrm{ph}}$ and $a_{\mathrm{CDOM}}$ components) and (2) the diffuse attenuation for downwelling irradiance $K_d$ (and the resulting nonwater total constituent backscattering $b_{\mathrm{bt}}$ due to particles, large molecular weight molecules, and colloid suspensions).[1–3] In addition to the two laser wavelengths, the third degree of freedom required for retrieval of three IOPs is furnished by the temporal measurement.

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## 2. Theory of Retrieval of Absorption and Backscattering Coefficients with Dual-Wavelength Elastic-Backscattering Lidar

First, the absorption retrieval is described in Subsection 2.A followed by a description of the backscattering retrieval in Subsection 2.B. The required lidar transmitter, receiver, and airborne data-acquisition considerations are reviewed in Section 3.

### A. Theory of Retrieval of Absorption Coefficients of Phytoplankton and Chromophoric Dissolved Organic Matter from Elastic Lidar Returns

It has been shown[5] (e.g., see Figs. 3 and 4 in Ref. 5) that, regardless of lidar field of view (FOV), the lidar attenuation coefficient $k_{\text{lidar}} \rightarrow a$, the total absorption coefficient, as the lidar range $\zeta \rightarrow 0$. The parameter $k_{\text{lidar}}$ is the negative slope of $2 \ln[P(\zeta)/P(\zeta_{\text{reference}})]$ versus $\zeta$ where $P(\zeta)$ is the received lidar signal from range $\zeta$ and $\zeta_{\text{reference}}$ is a shoaler reference range near the air–water interface.

Conceptually then, for two lidar transmit wavelengths $\lambda_1$ and $\lambda_2$, the absorption coefficients at $a(\lambda_1)$ and $a(\lambda_2)$ are retrievable from $k_{\text{lidar}}(\lambda_1)$ and $k_{\text{lidar}}(\lambda_2)$ in the limit of null depth. But the primary component absorbers in the ocean are phytoplankton, CDOM, and water such that, at any wavelength $\lambda$, $a(\lambda) = a_{\text{ph}}(\lambda) + a_{\text{CDOM}}(\lambda) + a_{\text{water}}(\lambda)$. Thus the two elastic lidar returns can potentially provide $a(\lambda_1)$ and $a(\lambda_2)$ such that

$$\begin{aligned} a_{\text{ph}}(\lambda_1) + a_{\text{CDOM}}(\lambda_1) &= a(\lambda_1) - a_{\text{water}}(\lambda_1), \\ a_{\text{ph}}(\lambda_2) + a_{\text{CDOM}}(\lambda_2) &= a(\lambda_2) - a_{\text{water}}(\lambda_2), \end{aligned} \tag{1}$$

where the quantities on the right side of Eqs. (1) are known. With four unknowns on the left side of Eqs. (1), IOP models allow the number to be reduced to two unknowns. For the CDOM absorption coefficient $a_{\text{CDOM}}$, a viable model[1–3] is $a_{\text{CDOM}}(\lambda_i) = a_{\text{CDOM}}(\lambda_d)\exp[-S(\lambda_i - \lambda_d)]$ where $S$ is the spectral slope of the CDOM absorption coefficient and has a value of ~0.017/nm for coastal and shelf waters of the western North Atlantic Ocean.[3] In passive (solar reflectance) nonlidar research[1–3,6] with blue and green passive bands, a phytoplankton model is generally used such as $a_{\text{ph}}(\lambda_i) = a_{\text{ph}}(\lambda_g)\exp[-(\lambda_i - \lambda_g)^2/2g^2]$ where $g$ is the Gaussian spectral width[6] having a range of 60–100 nm and a nominal value[3] of ~70 nm). Here $\lambda_d$ and $\lambda_g$ are chosen as the reference wavelengths for CDOM and phytoplankton, respectively, and $i = 1, 2$ identifies $\lambda_1$ or $\lambda_2$. However, because the Gaussian model is not a particularly good choice for UV wavelengths, (1) a more general function $a_{\text{ph}}(\lambda_i) = a_{\text{ph}}(\lambda_g)g(\lambda_i, \lambda_g)$ is used in the theory below and (2) $a_{\text{ph}}(\lambda_i)$ table look-up values can actually be used in the computation if desired. Then the two-row matrix of equations in Eqs. (1) becomes

$$a_{\text{ph}}(\lambda_g)g(\lambda_i, \lambda_g) + a_{\text{CDOM}}(\lambda_d)\exp[-S(\lambda_i - \lambda_d)] = a(\lambda_i) - a_{\text{water}}(\lambda_i), \tag{2}$$

having only two unknowns at their reference wavelengths $a_{\text{CDOM}}(\lambda_d)$ and $a_{\text{ph}}(\lambda_g)$. Equation (2) can now be solved by simple algebraic substitution or by linear matrix inversion,[1–3,6] i.e., Eq. (2) can be written in matrix form as

$$\mathbf{Dp} = \mathbf{h}, \tag{3}$$

whose solution is $\mathbf{p} = \mathbf{D}^{-1}\mathbf{h}$. Here the hydrospheric vector $\mathbf{h}$ is the column vector given by the right-hand side of Eq. (2). The IOP state vector is $\mathbf{p} = [a_{\text{ph}}(\lambda_g), a_{\text{CDOM}}(\lambda_d)]^T$, where $T$ denotes the transpose and $\mathbf{D}$ is the data model matrix.[1–3,6] Note that the models for $a_{\text{ph}}$ and $a_{\text{CDOM}}$ must properly represent the correct relative values at $\lambda_1$ and $\lambda_2$, otherwise significant errors can occur in the retrievals.[1–3,6]

The $a_{\text{CDOM}}$ spectral model is robust throughout the near UV and visible. The $a_{\text{ph}}$ Gaussian model is known to be reliable at 412, 490, and 555 nm,[1–3,6] but the suggested $a_{\text{ph}}(\lambda_i) = a_{\text{ph}}(\lambda_g)g(\lambda_i, \lambda_g)$ may require some initial adjustment to provide accurate relative values at $\lambda_1$ and $\lambda_2$.

Thus, if a dual-channel elastic lidar system can be configured to retrieve the total absorption at each laser wavelength, then the absorption coefficient of the two principal oceanic constituent absorbers $a_{\text{ph}}(\lambda_g)$ and $a_{\text{CDOM}}(\lambda_d)$ can be retrieved.

### B. Retrieval of the Backscattering Coefficient

It has also been shown[5] that, as the lidar depth approaches some large value (depending on water type), $k_{\text{lidar}} \rightarrow K_d$, the diffuse attenuation for downwelling irradiance. The findings indicate that a sensing depth of 30–50 m will allow a retrieval of $K_d$ in coastal waters. (Similarly, findings suggest that sufficient multiple scattering can occur within 10 m in turbid harbor waters to allow the $K_d$ retrieval there.)[5] Note that the same backscatter waveform is being used: the shallow portion for $a$ and the deeper portions for $K_d$.

Once $K_d$ has been retrieved, the backscattering can be estimated from the approximate relationship $K_d = a + b_b$ where $a$ is known from Subsection 2.A above and the total backscattering is $b_b = b_{\text{bt}} + b_{b,\text{water}}$. Or the nonwater total constituent backscattering $b_{\text{bt}}$ is

$$b_{\text{bt}}(\lambda_i) = K_d - a(\lambda_i) - b_{b,\text{water}}(\lambda_i), \tag{4}$$

where, again, $i = 1, 2$ identifies $\lambda_1$ and $\lambda_2$. Only one wavelength is needed to retrieve $b_{\text{bt}}$. However, if the nonwater total constituent backscattering $b_{\text{bt}}$ is retrieved at both wavelengths, then both $b_{\text{bt}}(\lambda_1)$ and $b_{\text{bt}}(\lambda_2)$ can be used to examine the variability of the exponent $n$ in the widely used backscattering model[1–3,7] $b_{\text{bt}}(\lambda_i) = b_{\text{bt}}(\lambda_b)[(\lambda_b)/(\lambda_i)]^n$ where $\lambda_b$ is a reference wavelength. The $n$ factor exponent should be cautiously compared with those values used for passive satellite IOP retrievals at wavelengths different from $\lambda_1$ and $\lambda_2$. In expression 4, the error in $b_{\text{bt}}$ is strongly driven by the fact that it is essentially being obtained from the difference of two relatively large numbers, $K_d$ and $a$.

## 3. Lidar Hardware Considerations

### A. Lidar Transmitter

A robust frequency-doubled and frequency-tripled 1064-nm Nd:YAG laser is a strong candidate because such a dual-wavelength inelastic lidar system[4] is now in operation at 355 and 532 nm to concurrently probe the oceanic water column. The 355- and 532-nm wavelengths are both absorbed by phytoplankton because chlorophyll fluorescence emission is observed at ~683 nm by such airborne lidar systems. CDOM is absorbed at both wavelengths because its absorption spectrum spans the entire 355–532-nm range. Neither the 532- nor the 355-nm laser wavelengths is optimal for retrieval of the three principal oceanic IOPs, and a possible concern is sufficient penetration depth of the 355-nm beam. However, robust water Raman emission at ~402 nm and concurrent chlorophyll fluorescence emission at ~683 nm strongly suggests that the sensing depths needed for absorption and diffuse attenuation coefficient at 355 nm are adequate.

Many laser wavelengths are available. Particularly promising are lasers having suitably separated wavelength pairs provided by optical parametric oscillators, or optical parametric amplifiers could also be used so long as their chosen wavelengths fall within the broad near-UV and visible absorption bands of CDOM and phytoplankton. Also, a four-wavelength copper vapor laser lidar system has been proposed for retrieval of various IOPs (but the analyses here strongly suggest that only two wavelengths are actually required for satellite validation purposes).[8]

Because $k_{\mathrm{lidar}}$ at null depth is required, then a narrow transmit pulse width, ~1 ns[5], is suggested for good depth resolution. It follows that a wide-bandwidth receiver is also required. This combination is suggested to enable separation of the strong Fresnel surface reflection from the desired null depth return component.

### B. Lidar Receiver

Regardless of the FOV, $k_{\mathrm{lidar}} \to a$, in the limit of vanishing depth. However, Fig. 3 in Walker and McLean[5] shows that the retrieval of $a$ will be highly variable for narrow FOVs (~1 mrad) in the null depth limit because of the large slope of $k_{\mathrm{lidar}}$ versus depth. For the baseline wide FOV (100 mrad),[5] the slope of the $k_{\mathrm{lidar}}$ versus depth graph is much smaller suggesting that a reasonable estimate of $a$ could be obtained at a depth of ~1–2 m. Furthermore, 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.

The recommendation of a wide-FOV lidar drives the design of the entire lidar system but especially the receiver. The baseline[5] FOV of ~100 mrad (~5.7°) will allow considerable solar-induced background noise during daylight hours. (Daytime operation is dictated by the need to conduct airborne validation flights during daylight satellite passage.) Several potential detector configurations may allow wide-FOV operation during daytime hours: (1) a segmented photomultiplier tube, (2) digitally controlled variable irises, and (3) a multiple FOV (MFOV) optic whose individual FOV segments total ~100 mrad but are individually small enough to allow daytime operation typical of oceanic fluorosensor lidars.[4] Systems have been built[9] that use 32 separate annular concentric ring segments on a rotating aluminized glass disk synchronized with a 100-Hz laser for ground-based MFOV atmospheric lidar studies of clouds. A synchronized disk MFOV configuration has the advantage of requiring only a single photodetector and waveform digitizer but it suffers from the lack of simultaneity of the measurements. This nonsimultaneity disadvantage can be mitigated by concurrently flying passive visible ocean color and infrared radiometers[1,2,4] to identify water mass variability during data acquisition (and subsequent analyses). Simultaneous MFOV sampling can be accomplished by use of concentric annular ring fiber-optic segments routed to 32 separate photomultiplier tubes, but such a system would be quite expensive and also challenging to calibrate. Fiber-optic MFOV methods have been used in atmospheric lidars.[10] (4) NASA's Airborne Oceanographic Lidar (AOL) views ~450 cm$^2$ (a ~30 cm × ~15 cm oval) of ocean surface area[4] from a 150-m altitude corresponding to $2\theta_{\mathrm{rcvr}} \sim 2$ mrad. If the same area of ocean is viewed over a $2\theta_{\mathrm{rcvr}} \sim 100$-mrad FOV then a 15 m × 0.3 cm strip of ocean imaged on a photomultiplier tube can potentially accomplish the FOV requirement. A variable-width slit (such as supplied with the first-generation AOL instrument) would allow robust FOV adjustment during initial testing because a FOV <100 mrad may actually be required. This configuration is quite similar to a radial FOV suggested by Wright.[11]

The minimum sensing depth needed to retrieve $K_d$ depends on the water mass type. Because the water mass type may not be known, the signal variability between each MFOV segment may allow empirical relationships to define the depth needed to retrieve $K_d$. Additional correlative information from ancillary passive visible and infrared radiometers may also allow improved definition of the water mass and thereby the sensing depth required for $K_d$.

Perhaps the most practical problem that must be addressed in an elastic-backscattering lidar system is the strong and highly variable Fresnel reflectance at the air–water interface. The operation of an oceanic lidar system[1,2,4] at an off-nadir angle of ~1°–4° is sometimes effective to reduce the amplitude of this reflection without compromising the analyses. New methods are being developed to minimize the variability caused by these reflections.[11]

### C. Data Acquisition and Analysis

The elastically backscattered pulse energy acquired by the receiving telescope and spectrometer optics must be recorded by a time–waveform digitizer. A high-resolution time digitizer is an important component of the data-acquisition system for each elastic lidar spectral band to accurately define the sensing depth. Commercially available time digitizers are sufficient for implementation of the methods discussed here.

Before any parameters are retrieved it is important to remove artifacts from the lidar data. Recall that the received temporal-resolved (depth-resolved) lidar data are a convolution of (a) the desired in-water return signal, (b) the finite pulse width of the laser transmitter, (c) the finite bandwidth of the lidar receiver electronics, and (d) pulse broadening due to the sea state within the receiver FOV.[12] The signal components in (b) and (c) induce a time spread in the unprocessed waveform and must be removed to yield the desired signal. Items (b) and (c) can be simultaneously removed from the unprocessed lidar return signal by the deconvolution of the flat target response[12] of the lidar to yield the actual in-water temporal backscattering waveforms. (Flat target response data can be obtained during preflight ground testing or by data-acquisition flights over flat sandy beaches.) The sea-state contribution can be corrected,[12] but, better yet, sea-state effects can be minimized when the airborne data are acquired under low-wind and sea-state conditions.

## 4. Summary and Discussion

Analytic lidar equations[5] based on a robust beam-spread function with time dispersion[13] show that, regardless of FOV, $k_{\text{lidar}} \rightarrow a$ in the limit of vanishing depth. For hardware implementation, a narrow-FOV configuration is not recommended because of high uncertainty in $k_{\text{lidar}}$ 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.

Dual-laser lidars yield two total absorption values that can be solved by linear methods to provide the main oceanic absorption coefficients: phytoplankton absorption coefficient $a_{\text{ph}}$ and CDOM absorption coefficient $a_{\text{CDOM}}$.

In the limit of large depth, the wide-FOV lidar yields $K_d$, the diffuse attenuation coefficient for downwelling irradiance. $K_d$ provides the total backscattering coefficient by $b_b = K_d - a$ or the total constituent backscattering from $b_{\text{bt}} = K_d - a - b_{b\text{,water}}$. Thus the three main oceanic IOPs ($a_{\text{ph}}$, $a_{\text{CDOM}}$, $b_{\text{bt}}$) are retrievable with a dual-laser wide-FOV elastic-backscattering lidar having wide-bandwidth time and depth digitizers. These three IOPs are the same as obtained from satellite-derived passive water-leaving radiances[1–3] and, accordingly, can be validated by airborne underflights with a dual-laser wide-FOV elastic-backscattering lidar system. Because the optical coefficients are derived for two different depths, this implies that the water column is uniformly mixed. If this oceanic physical condition is not met, then undetermined errors should be expected. Undesired water column nonuniformity can be detected when the entire water column return is analyzed.[14]

The Walker and McLean[5] findings also show that, in the limit of small FOV, $k_{\text{lidar}} \rightarrow c$, the beam attenuation, for certain intermediate depths between $\zeta \sim 0$ and $\zeta = \zeta_{K_d}$ required for the respective retrieval of $a$ and $K_d$. If the proper depth for beam attenuation $\zeta_c$ can be accurately determined, then $c$ can be further used to retrieve the forward-scattering coefficient $b_f = c - a - b_b$ where $a$ and $b_b$ were previously determined at $\zeta \sim 0$ and $\zeta = \zeta_{K_d}$, respectively. The $b_f$ optical property is infrequently retrieved by remote sensing but is required in newer-generation remote sensing reflectance models[15,16] that are based on the radiative transfer equation. The beam attenuation coefficient alone is a highly important IOP because it is strongly correlated with particulate organic carbon,[17,18] a notable component of the global oceanic carbon cycle. Other researchers[19] findings agree with Walker and McLean[5] for the so-called coherent or beam attenuation component of the lidar return.

Even after several decades, the most fundamental elastic lidar measurement, depth sounding, is still performed with considerable attention to details.[20–22] Thus one should not expect instant success with the IOP retrieval methods proposed here. Inelastic lidar fluorosensors are less prone to some of the challenges of elastic lidars because their redshifted returns are volumetric and show significantly less air–water interface effects. Accordingly, nonempirical radiative-transfer-based algorithms must eventually be sought for the inelastic lidar return signals. In this regard, it is recommended that the Walker and McLean[5] analyses be extended to the OH-stretch water Raman signal now observed routinely with airborne oceanic lidars.[1–4] Then a single-laser lidar could be used to retrieve the three principal oceanic IOPs: phytoplankton and CDOM absorption and the constituent backscattering coefficients. For example, a 532-nm lidar should have at least two receiver channels: the usual 532-nm elastic channel and an inelastic ~3250-cm$^{-1}$ OH-stretch water Raman band at ~645 nm. A 355-nm laser lidar should have at least three receiver channels: the usual 355-nm elastic channel, a water Raman band at ~402 nm, and a 450-nm channel to provide for CDOM fluorescence removal from the 402-nm Raman emission band. Because the 532- or 355-nm laser wavelengths are nonoptimal, a tunable laser set to ~443 nm for phytoplankton and CDOM absorption would seem ideal and would produce a water Raman emission at ~518 nm. A third band at perhaps ~490 nm (to acquire CDOM fluorescence to produce corrections for the Raman band) would be required. Laboratory experiments are recommended to finalize these band selections.

To implement the methods outlined here, commercially available lasers, telescopes, and time digitizers are generally suitable. However, initially, this proposed lidar IOP retrieval concept might be tested with only a single wide-FOV receiver during nighttime flights of an existing airborne lidar. Such a configuration would require minimum hardware and may provide basic information that would allow a daytime wide-FOV system to be implemented. For example, a single wide FOV for nighttime flight could potentially be implemented on an existing lidar such as the NASA AOL with relative ease. The NASA AOL-III[4] is a dual-laser lidar (and carries ancillary passive ocean color and infrared radiometers) and could conceivably be retrofitted with dual rotating disk MFOV segments to measure $a$ at both 355 and 532 nm during daytime. The AOL already possesses high-speed waveform digitizers to acquire lidar return waveforms for retrieval of both $a$ and $K_d$. These elastic retrievals at 355 and 532 nm would then complement the standard inelastic phytoplankton and CDOM fluorescence products.[1,2,4] Initially, during application of a dual-laser elastic lidar, the resulting IOP retrievals should be validated with both supporting ship measurements and inelastic fluorosensor lidar findings. However, it is also suggested and recommended that initial validation of the above elastic lidar-derived products be accomplished with an airborne passive nadir-viewing ocean color spectroradiometer. The NASA AOL's companion Airborne Diode Array Spectroradiometer (ADAS) is an example of a suitable spectroradiometer. The ultimate goal of satellite validation by use of an airborne active–passive (laser–solar) system is to achieve IOP closure (or consistency) among all four sensor products: satellite, airborne passive spectroradiometer, lidar inelastic, and lidar elastic. (Use of a passive radiometer to validate lidar retrievals is rather ironic because the reverse is the usual situation: the ADAS-derived IOP products are normally validated by the inelastic AOL fluorescence emissions.[1–3])

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