Beam attenuation coefficient retrieval by inversion of airborne lidar-induced chromophoric dissolved organic matter fluorescence. I. Theory

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It is shown that the oceanic beam attenuation coefficient can be retrieved from airborne laser-induced and depth-resolved chromophoric dissolved organic matter (CDOM) fluorescence. The radiative transfer equation (RTE) retrieval methodology does not require a laser beam spread function model since two CDOM fluorescence bands are used in conjunction with a beam attenuation spectral model, is self-normalizing since the CDOM absorption coefficient and laser beam irradiance are common to both fluorescence observational channels, and is enabled by the known isotropic phase function for CDOM fluorescence. Although this RTE analytical inversion theory is exact, the retrieval uncertainty is reduced by configuring the proposed lidar in the multiple-field-of-view beam attenuation mode to significantly diminish observation of multiple scattering. The theory can be applied over wide regions of the ocean's continental margins, estuaries, lakes, and rivers that are known to have sufficient CDOM.

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1. Introduction

Beam attenuation coefficients are a fundamental measurement in ocean optics and this is especially true since it contains all the component absorption and scattering.[1] Also, beam attenuation measurements have recently been closely linked to a major component of the global carbon cycle: particulate organic carbon (POC).[2,3] Since no airborne or satellite retrieval algorithms for beam attenuation or POC are presently available, efforts are needed to address this void. Once the airborne lidar beam attenuation is in place, then satellite algorithm development can be assisted by lidar through use of simultaneous airborne passive (solar) ocean color spectroradiometry.[4–9] Also, the same airborne methodology can later provide satellite algorithm validation by airborne underflights of ocean color satellite sensors.

Chromophoric dissolved organic matter (CDOM) is also an important carbon-containing constituent of the ocean that is not only a valuable active and passive tracer of the physical forcing of the ocean[6,7,10–12] but, as described herein, is a valuable constituent that allows retrieval of oceanic inherent optical properties. In the past one of the primary uses of lidar-induced CDOM fluorescence was for empirical determination of the CDOM absorption coefficient. The present radiative transfer equation (RTE) inversion effort is significantly less empirical and addresses the application of CDOM fluorescence to retrieval of the beam attenuation coefficient.

The theory derived herein is meant to complement a beam attenuation coefficient concept that uses the single-channel OH-stretch water Raman backscattering.[13] Compared with water Raman scattering, use of CDOM fluorescence for beam attenuation retrieval is more complex. For example, water Raman scattering is prompt with essentially no temporal or pulse broadening and has only a small temperature variability that can be ignored for beam attenuation retrievals; it also has a constant scattering coefficient. On the other hand, CDOM fluorescence has a temporal decay lifetime that can reach ~9 ns, has a regionally variable absorption coefficient (and associated fluorescence) that is dependent on assorted concentrations of molecularly variable chromophores and on the amount of solar irradiance and resulting photodegradation, and has a significant negative correlation with salinity[14] especially in coastal regions having low salinity runoff. As described in this paper, some of these issues are addressed through use of two CDOM spectral bands. (For remote Raman spectroscopy, a two-band option is not presently available since only the OH-stretch Raman band is strong enough for remote sensing.) Also, because it is prompt, the water Raman can be used to assist in the correction and removal of the temporal decay of CDOM fluorescence from the desired temporal decay (i.e., radiance variability with depth) caused by inherent water column attenuation. Concurrently, the lidar receiver electronic temporal decay characteristics can be removed. Thus the water Raman can simultaneously be applied to both the CDOM fluorescence decay and the receiver electronic pulse broadening.

The beam attenuation theory herein can be applied only in regions having CDOM such as continental shelves, estuaries, lakes, and rivers. However, these regions occupy considerable portions of the world's oceans. CDOM is sometimes called yellow substance,[5] and for simplification of the mathematical equations, the superscript or subscript Y is used in place of CDOM for simplification.

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4. Summary and Discussion

Beam attenuation coefficient retrieval methodology by RTE inversion of airborne laser-induced and depth-resolved CDOM fluorescence is given. Two fluorescence band segments chosen within the broad CDOM fluorescence emission spectrum allow a retrieval (1) without the need for a laser beam spread model and (2) that is self-normalizing. The self-normalization arises from the fact that the fluorescence in the spectrally separated bands has a common source term. Thus the source term is eliminated during the retrieval methodology leaving the equations dependent only on the measured spectral radiances. The inversion is further enabled by the known isotropic fluorescence phase function and further simplified by the known ratio of the CDOM fluorescence distribution function for the two observational bands. Two fluorescence channels eliminate the need for a BSF model that is required when one uses the single water Raman retrieval methodology.[13]

To minimize observation of multiple scattering, the lidar is configured in a MFOV BAM. The proposed MFOV lidar receiver allows extrapolation to null or 0° FOV to optimize the BAM application. The BAM also facilitates evaluation of the fluorescence source function integral as applied to a coaxial transmitter and receiver.

Monte Carlo radiative transfer studies, and acquisition of appropriate new airborne lidar data, are planned for continued study as well as validation of this beam attenuation method.

Appendix A: Development of the Radiative Transfer Equation for Lidar-Induced Fluorescence

This theoretical development for fluorescence is similar, but not identical, to the inclusion of water Raman in the RTE.

As will be subsequently seen below, the solution of the RTE is enabled by the fact that both the CDOM fluorescence spectral redistribution function and the phase function (isotropic) are known. Development is further facilitated by the highly monochromatic character of the laser transmitter; the known directionality of the laser beam emission; the highly collimated character of the laser transmitter; the pulsed nature of the laser output that allows the depth-resolved backscattered radiances to be measured; the MFOV and known directionality of the laser receiver; for the 355 nm laser, a good choice of spectral bands within the broad CDOM fluorescence spectrum (~355–600 nm) that avoids and therefore excludes interference from the water Raman scattering at ~402 nm; pulsed laser excitation and fluorescence detection separated such that encroachment of the laser radiance into the CDOM fluorescence spectrum is easily avoided; and the receiver detectors and phototubes that are ac coupled so that dc background from solar and sky radiance is rejected.

We establish a Cartesian coordinate system with the $+z$ axis vertically downward into the ocean and the x and y axes lying in the ocean just below the atmosphere–ocean boundary. Unit vectors pointing along the positive direction of these x, y, z axes are, respectively, $\mathbf{i}, \mathbf{j}, \mathbf{k}$. In a plane-parallel medium that includes inelastic (e.g., CDOM) fluorescence and elastic scattering, the in-water time-independent RTE is[1,28-30]

$$\cos\theta \frac{dL(z;\theta,\phi;\lambda)}{dz} = -c(z;\lambda)L(z;\theta,\phi;\lambda) + \int_0^{2\pi}\int_0^{\pi} \beta(z;\theta',\phi'\rightarrow\theta,\phi;\lambda) \times L(z;\theta',\phi';\lambda)\sin\theta' d\theta' d\phi' + \int_{\lambda'}\int_0^{2\pi}\int_0^{\pi} \beta^F(z;\theta',\phi'\rightarrow\theta,\phi;\lambda'\rightarrow\lambda) \times L(z;\theta',\phi';\lambda')\sin\theta' d\theta' d\phi' d\lambda', \quad \text{(A1)}$$

where $c(z, \lambda)$ is the beam attenuation coefficient at depth z for all absorption and scattering events at wavelength λ; $L(z; \theta, \phi; \lambda)$ is the radiance at depth z propagating and being observed in a direction specified by the polar angle θ, in water, measured with respect to the $+z$ axis, and ϕ is the azimuthal angle measured with respect to the $+x$ axis. (Primed θ' or ϕ' denote the incoming direction of source radiance at its wavelength λ'.) [Note that the required fluorescence radiance $L(z; \theta, \phi; \lambda)$ is (a) derived from the lidar temporal radiance measurement $L(t = 2zm/v; \theta, \phi; \lambda)$ where v is the velocity of light, t is the two-way elapsed time, and m is the index of refraction; (b) can be contaminated with other inelastic scattering such as water Raman; (c) contains intrinsic electronic temporal decay and CDOM fluorescence lifetime decay and a sea state all of which must be deconvolved; (d) the required spatial derivative of $L(z; \theta, \phi; \lambda)$ can be calculated by using standard methods to differentiate digital data itself or to fit the digital data to an exponential(s) or a polynomial and then execute the derivative.][31] Here $\beta(z; \theta', \phi' \rightarrow \theta, \phi; \lambda)$ is the volume scattering function describing the elastic scattering of radiance at wavelength λ from direction θ', ϕ' into direction θ, ϕ. And $\beta^F(z; \theta', \phi' \rightarrow \theta, \phi; \lambda' \rightarrow \lambda)$ is the volume scattering function describing the inelastic scattering (fluorescence) of radiance at wavelength λ' from direction θ', ϕ' into radiance at wavelength λ in the direction θ, ϕ. Note that, unlike water Raman scattering, the fluorescence volume scattering function $\beta^F(\mathrm{m}^{-1}\,\mathrm{sr}^{-1})$ is depth dependent and is thus shown in Eq. (A1) with depth dependency. Equation (A1) is valid for observational wavelengths λ and shorter wavelengths λ' where $\lambda' < \lambda$. (Superscripts or subscripts F and L denote fluorescence or the laser, respectively; when used as a subscript, L should not be confused with radiance.) The RTE of Eq. (1) does not include multiple scatter, i.e., photons that are scattered out of the transmitted beam and then again scattered back into the original transmit or receive paths. Thus this RTE will be applied to a lidar configured in a MFOV BAM to minimize observation of multiple scattering.