INVERSE PROBLEMS IN HYDROLOGIC RADIATIVE TRANSFER

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LONG-TERM GOALS

The long-term scientific goal of my research is to better understand the distribution of phytoplankton in the world's oceans through remote sensing their influence on the optical properties of the water.

OBJECTIVES

Optically, phytoplankton reveal their presence through their influence on the inherent optical properties (IOP's) of the water. The main effect of phytoplankton is to increase the absorption of light by virtue of the strong absorption by their photosynthetic (chlorophyll a) and accessory pigments. A secondary effect is to increase the backscattering coefficient of the medium in a manner that depends on the concentration of pigments. Although techniques for measuring the absorption coefficient directly (e.g., in-situ AC9 measurements or in-vitro filterpad absorption) are becoming accepted by the scientific community, laboratory techniques for measuring backscattering are tedious and subject to error, and in-situ techniques for backscattering are in their infancy. In addition, in most in-situ measurements the volume of medium that is sampled is small and may not be representative of the whole water body, even in a homogeneous medium. Thus, in the past, there has been considerable effort devoted toward indirectly inferring these IOP's by virtue of their affect on the apparent optical properties (AOP's), e.g., the diffuse reflectance of the water (the color of the water) or the downwelling irradiance attenuation coefficient. These AOP's are perhaps the most frequently measured quantities in hydrologic optics. Clearly, interpretation of such observations requires a detailed understanding of the influence of phytoplankton on the IOP's, and their link to the AOP's.

The IOP $\leftrightarrow$ AOP link forms the focus of the present research. In particular, our research is centered on deriving the IOP's from measurements of the AOP's. This is an example of the inverse problem of radiative transfer. It is important in that IOP's determined from AOP's are, by definition, sampled at a scale appropriate for radiative transfer, and for remote sensing. Also, the retrieved IOP's possess the attribute that when combined with the radiative transfer equation, they reproduce the measured AOP's. The table below summarizes in matrix form inverse problems relevant to hydrologic optics. Our goal is to fill in the uncompleted elements of the matrix.

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Matrix of Inverse Problems Relevant to Hydrologic Optics

Problem	Water Body	
	Homogeneous	Stratified
Elastic (Depth = ∞)	✔	✔
Elastic (Depth < ∞)	✔	✚
Raman (Depth = ∞)	✘	✘
Raman (Depth < ∞)	✚	✚
Fluor. (Depth = ∞)		
Fluor. (Depth < ∞)		

✔: Inverse solution completed earlier
✘: Inverse solution completion reported here
✚: Inverse solution to be studied during the next reporting period

In earlier research (Gordon and Boynton, 1997, 1998), we focused on developing methods for deriving the vertical profiles of the absorption and backscattering coefficients from measurements of the vertical profiles of downwelling irradiance and either upwelling radiance or upwelling irradiance in the absence of inelastic processes (✔). However, as the presence of inelastic processes can make a significant contribution to the in-water light field (Stavn and Weidman, 1988; Gordon 1999), we extended that study to include the influence of Raman scattering in the inversion algorithm, i.e., to retrieve the IOP's from the AOP's when they are contaminated by Raman scattering (✗). We chose to look at Raman scattering as opposed to other inelastic processes (e.g., fluorescence of dissolved organic matter) because the Raman scattering cross sections are known (Bartlett, et al., 1998).

APPROACH

Our approach for including Raman scattering in the water body is to use the basic algorithm developed by Gordon and Boynton (1998), to retrieve the absorption and backscattering coefficients of a *vertically stratified* water body. We refer to this algorithm as the elastic inversion algorithm (EIA). However, as the AOP's that are entered into the algorithm are corrupted by Raman scattering, we use irradiances measured at the Raman excitation wavelength to estimate the Raman source function and then its contribution at the emission wavelength of interest. This contribution is subtracted from the irradiances at the emission wavelength and the EIA applied to the remainder. Because the Raman contribution to the irradiance at the emission wavelength depends on the emission wavelength IOP's, this process must be carried out iteratively, i.e., new estimates of the IOP's are used with the source function to develop new estimates of the Raman contribution, etc.

WORK COMPLETED

Using the approach described above, we developed an algorithm for retrieving vertical profiles of the absorption and backscattering coefficients, in the presence of Raman scattering in a vertically stratified ocean from measured vertical profiles of the AOP's at both the emission and Raman excitation wavelengths. Details of the Raman inversion algorithm (RIA) are provided in Boynton and Gordon (1999).

RESULTS

As an example of the performance of the RIA we used the Morel and Gentili (1993) model and the pigment profile in Figure 1 to provide a set of IOP's to generate synthetic data. The pseudodata were generated at 460, 544, and 666 mn. We assumed there was no Raman contribution at 460 nm, but Raman scattering from 460 to 544 nm was included in the 544 nm light field, and Raman scattering from 544 to 666 was included in the 666 nm light field. The data at 666 nm were first inverted using just the EIA algorithm yielding the triangles in Figure 2 for $a(z)$ and $b_b(z)$. Note that the error in $a(z)$ is as much as 20% and the error in $b_b(z)$ reaches a factor of 10. Using the Raman inversion algorithm (RIA), these errors are reduced to 1-2% for $a(z)$ and about 20% for $b_b(z)$. This improvement is typical of the performance of the RIA in cases where the Raman contribution to the light field is large. It is interesting to note that the Raman contribution from 544 nm to the total upwelling irradiance (666 nm) at 12 m in Figure 2 is over 90%. The algorithm breaks down as it must when the Raman contribution overwhelms the elastic contribution, because it is then impossible to estimate the Raman contribution with sufficient accuracy. As in the EIA, an attractive feature of the RIA is that the results are nearly independent of the scattering phase function assumed for the medium in the inversion process.

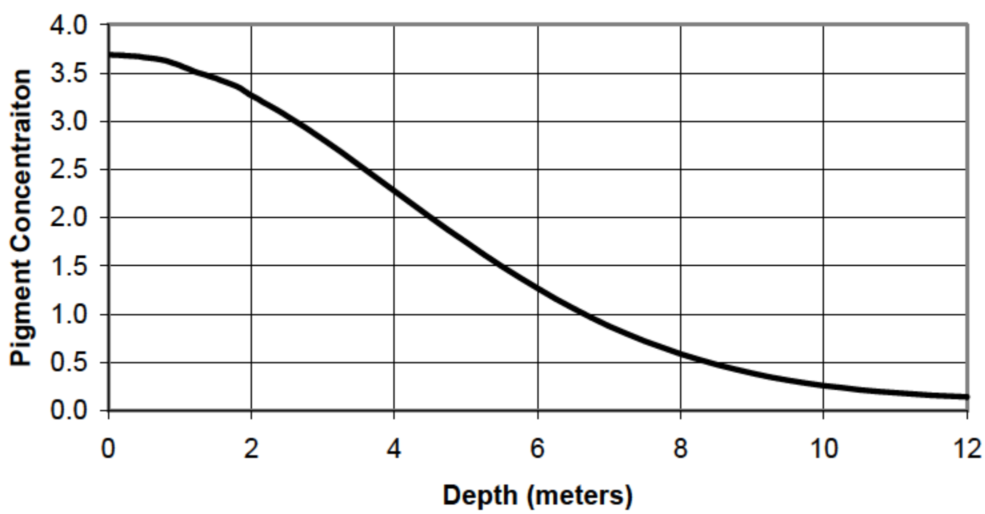

Figure 1: The pigment concentration (in mg/m^3) used to test the Raman inversion algorithm.

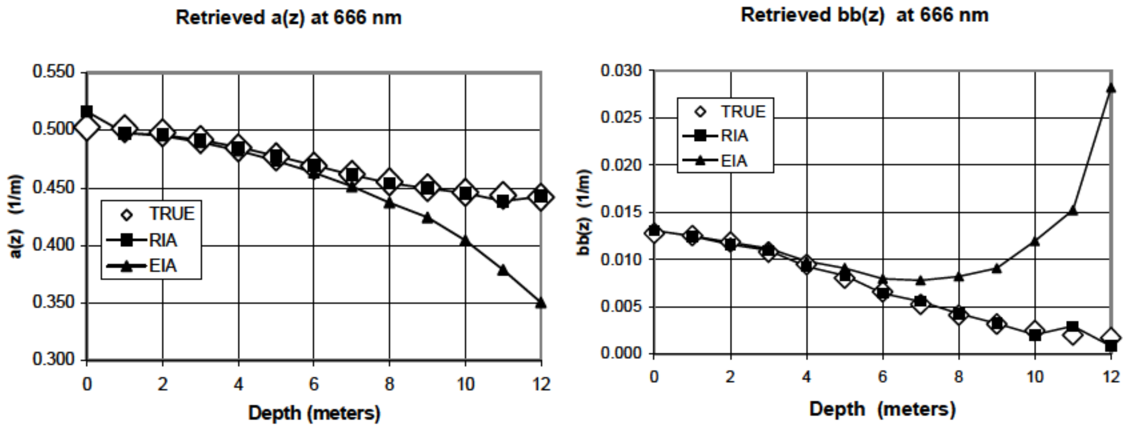

Figure 2: Performance of the Raman inversion algorithm (RIA) in retrieving a(z) and $b_b(z)$ compared with the elastic inversion algorithm (EIA) for the pigment profile in Figure 1.

IMPACT/APPLICATIONS

We believe that these algorithm will be of significant utility for processing existing and future experimental irradiance profile data to estimate the absorption and backscattering coefficients, and their relationship to constituent concentrations, for use in ocean color remote sensing algorithms. Furthermore, the algorithm provides IOP's that are, by definition, sampled at a scale appropriate for radiative transfer, and therefore, will be of significant value for examining questions of closure concerning traditional IOP-instruments that sample at scales of a few cubic centimeters.

TRANSITIONS

We have prepared versions of the EIA (most useful in the green and blue regions of the spectrum) to run on work stations using Linux (GNU Fortran) or Windows NT or 95/98 (PowerStation 4 Fortran). The latter has been provided to H. Sosik for testing.

RELATED PROJECTS

We are working with J. Mueller and J.R.V. Zaneveld to compare our estimates of absorption and backscattering profiles with direct measurements using in-situ instrumentation. We expect this work will contribute to AOP-IOP closure. We are developing a bi-directional model of the water-leaving radiance (including Raman contributions) for Case 1 waters. This will be used in processing MODIS imagery, and is funded by NASA.

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