

TESTING A NEW REMOTE SENSING REFLECTANCE ALGORITHM TO ESTIMATE ABSORPTION AND SCATTERING IN CASE 2 WATERS

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ABSTRACT

We examine absorption (a), scattering (b), and remote sensing reflectance (Rrs) relationships in coastal waters. A recently described inversion algorithm to estimate a and b from Rrs is refined and tested with data from a variety of turbid coastal zones. The algorithm is based on the slope of Rrs in the near-infrared (IR) region of the spectrum. The reflectance difference Rrs715-Rrs735 correlates well with scattering, because total absorption at these wavelengths is due entirely to absorption by pure water (absorption by dissolved organic matter, detritus, and pigments is negligible). Before calculating a and b, we partition the total measured Rrs into surface-reflectance (with sun glint and reflected sky light terms) and water-reflectance components. We form a combined C_b term that represents the numerator of $Rrs = C \cdot b_b / a$. The water Rrs value (total measured Rrs - surface component) is coupled with the C_b735 value and a shape factor for b_b to estimate spectral absorption. Spectral scattering is estimated from an empirical relationship based on Rrs715-Rrs735. Estimates can be refined if *in situ* data are available. The algorithm was developed and tested using data from thirteen experiments at five U.S. coastal locations collected over a two-year period and representing a variety of absorption and scattering regimes. Measured and modeled absorption and scattering coefficients agree favorably in both magnitude and spectral shape. Error analyses are presented.

INTRODUCTION

Remote sensing reflectance (Rrs), the ratio of upwelling water radiance (L_u) to downwelling surface irradiance (E_d) has been linked to the absorption (a) and scattering (b) characteristics of the water. These inherent optical properties (IOPs) of the water have far-reaching implications in a variety of fields, including: remote sensing (penetration depth); phytoplankton ecology and carbon budgeting (biomass and productivity models); heat flow estimates (mixed-layer models); and naval applications (swimmer visibility estimates and laser penetration depth). In addition, spatial and temporal variations in the bio-optical fields themselves provide valuable stand-alone insight into a variety of oceanographic processes, such as river discharge, surface circulation patterns, fish distributions, and sediment transport. Thus, rapid, accurate estimation of these optical parameters is important, and above-water Rrs measurements from aircraft or satellite sensors offer the advantage of synopticity. In-water measurements of the light field or the absorption/scattering properties of the water are more direct, but suffer from the disadvantages of point measurements.

In addition, accurate in-water optical measurements are difficult to make for several reasons. Ship and instrument shading must be reduced or accounted for with correction procedures. In turbid, coastal waters, light is attenuated rapidly with depth, and the attenuation length may be shorter than the length of the instrument, so slight changes in sensor depth radically affect the measurements. Also, it is difficult to measure radiances right below the sea surface, and the in-water radiances must also be pushed up through the air-sea interface for comparison with satellite-recorded water-leaving radiance measurements. For these reasons, a number of investigators use above-water reflectance measurements to derive estimates of in-water optical properties.

Above-water reflectance measurements are not without serious measurement problems as well, however. Measurement angles strongly affect derived reflectance values and must be consistent during data collection. Surface reflectance (sun glint and reflected sky and cloud light) contaminates the measured signal and must be partitioned and removed. So, before we can hope to solve the inversion problem of deriving water IOPs from R_{rs} measurements, we must remove the surface reflectance signal from the total, measured R_{rs} values. Previously, we have described new methods that utilize either polarization measurements or subsurface reflectance measurements collected with a submerged fiber-optic probe^{1,2} to remove surface effects. However, unless the polarization/probe measurements are collected at each station along with spectral a and b measurements, average values for the magnitude of the surface reflectance must be used.

We present a correction scheme for above-water measurements of R_{rs} , to remove surface-reflected sunglint and sky/cloud light from the total R_{rs} signal. We utilize sky radiance measurements (commonly collected during most standard R_{rs} measurement protocols) coupled with the shape of spectral scattering (modeled or measured) and *in situ* absorption measurements at a single wavelength (412 nm, determined from AC9 or filter pad/DOM measurements) to achieve the surface correction. We also test a new inversion algorithm to calculate spectral absorption and scattering from the reflectance difference at 715 and 735 nm.

METHODS

Thirteen surveys were conducted over a two-year period at five locations representing a variety of environments, including both highly-scattering and highly-absorbing waters (off coastal Virginia, California, North Carolina, Mississippi, and Alabama). Measurements included spectral reflectance, a , and b .

The above-water reflectance measurements were collected with a 512 channel fiber optic Analytical Spectral Devices (ASD) field spectroradiometer with a 1.4 nm spectral sampling interval. At each station, five sky, reference, and water spectra were recorded and averaged during post-processing. Measurement integration times were optimized for each target to maximize signal. R_{rs} values (total, without surface corrections) are derived by referencing the measured water counts to counts from a gray Spectralon standard of known reflectance.

To check the surface reflectance correction for the above-water R_{rs} measurements, a fiber optic extension cable was attached to the ASD unit and submerged just below the surface of the water. This provides a direct measurement of the upwelling

water radiance, but without the confounding effects of surface reflectance and radiance transfer through the air/sea interface. The subsurface measurements were collected from a dock at a test station; the water surface was flat so we could maintain a high degree of control on probe tip submersion depth (~ 2 cm) and measurement angles (~ 30° from vertical).

Surface measurements of a and b at nine wavelengths were collected at each station with a WetLabs AC9 meter. We applied temperature and scattering corrections³ to the absorption measurements and added pure water absorption coefficients⁴, to yield total, corrected absorption coefficients. An estimate of b is derived through subtraction of the beam attenuation and absorption values. The AC9 a and b values were averaged over the upper 1.5 m of the casts for comparison with the surface values derived from the inversion of the R_{rs} values.

Filter pad analyses of surface water samples were performed at several stations using the ASD instrument, to partition the total absorption coefficient into particulate and DOM (dissolved organic matter) components, and to provide an additional check on the AC9 absorption values. The GF/F filters were mounted on a glass holder, inserted in a light-tight black aluminum box, and illuminated via a fiber optic cable. Light transmitted through the filter was recorded by the ASD. DOM absorption was calculated from light transmission measurements on the filtrate in a 10 cm cuvette in the black box.

CORRECTION FOR SURFACE REFLECTANCE

Before we can apply inversion algorithms to estimate water IOP's from above-water R_{rs} measurements, we must first remove sky light, sun glint, and any surface-reflected cloud light that contaminates the measurement of R_{rs} . This requires partitioning the total R_{rs} into water, sky, and glint components and subtracting the unwanted sky/cloud and glint signals from the total, to yield water R_{rs} , which is used in the slope algorithm. For our surface correction, we assume that the total, measured, above-water R_{rs} signal can be separated into a spectrally flat sunglint component (B) and a spectrally variable sky/cloud light component ($A \cdot R_{rs,sky}$). The combined correction terms are calculated at 735 nm and 412 nm (diff1 and diff2, respectively, in Figure 1), then the two equations in Figure 1 are solved simultaneously to calculate the two unknowns (the A and B coefficients).

INVERSION ALGORITHM

We describe a new algorithm to estimate a and b in turbid, coastal waters from above-water reflectances in the near-infrared wavelength region (715-735 nm). The rationale behind the algorithm development stems from the well-known reflectance relationship $R_{rs}(\lambda) = C \cdot b_b(\lambda) / a(\lambda)$, and from the wavelength dependence of the various components of absorption and how they contribute to the total absorption coefficient. In the 715-735 nm waveband, there is a strong linear relationship between scattering and reflectance, because absorption is due mainly to pure water, and the spectral absorption coefficient of pure water is well-defined⁴. Absorption by phytoplankton pigments, detritus, and dissolved organic matter (DOM) is negligible at these wavelengths. Low

signal in the 715-735 nm wavelength range in clear water precludes the use of this algorithm in open-ocean, Case 1 regions, however.

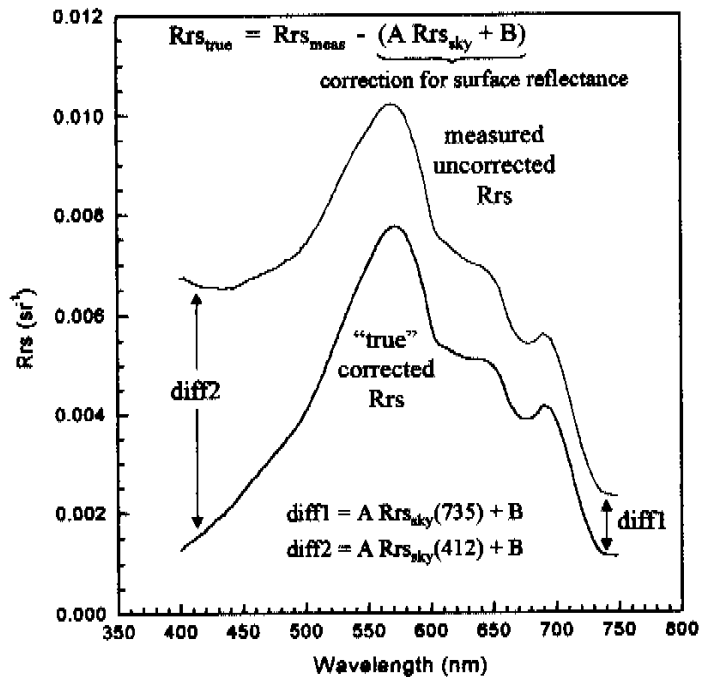


Figure 1. Schematic of the surface correction algorithm.

The C term is equal to $(f \cdot t^2)/(Q \cdot n^2)$, where f is an empirical constant (equal to about 0.33), t is the air/sea transmission coefficient, n is the seawater index of refraction, and Q is the ratio of upwelling irradiance to upwelling radiance. C has been considered a constant by most investigators, although it is known to vary with measurement angle, sun angle, and wind speed⁵. The relative curve shape for a typical, coastal Rrs signature is shown in Figure 2, along with representative curve shapes for the various components that interact to produce the observed Rrs signature. Note the various curve shapes in the hatched area; the sharp decrease in reflectance at wavelengths over 700 nm is controlled by the sharp increase in pure water absorption and by the magnitude of the backscattering.

To calculate spectral b_b , we use either a linear, empirical relationship between ΔRrs ($Rrs_{715} - Rrs_{725}$) and backscattering, or, if AC9 values are available, we calculate the C term from coupled Rrs and AC9 measurements. To estimate spectral a, we compute a combined $C \cdot b_b$ term at 735 nm, combine this with a "shape" factor (measured or modeled) for spectral b_b , then solve for a from Rrs. The processing flow of the combined algorithm (surface reflectance correction and inversion algorithm) is summarized in figure 3.

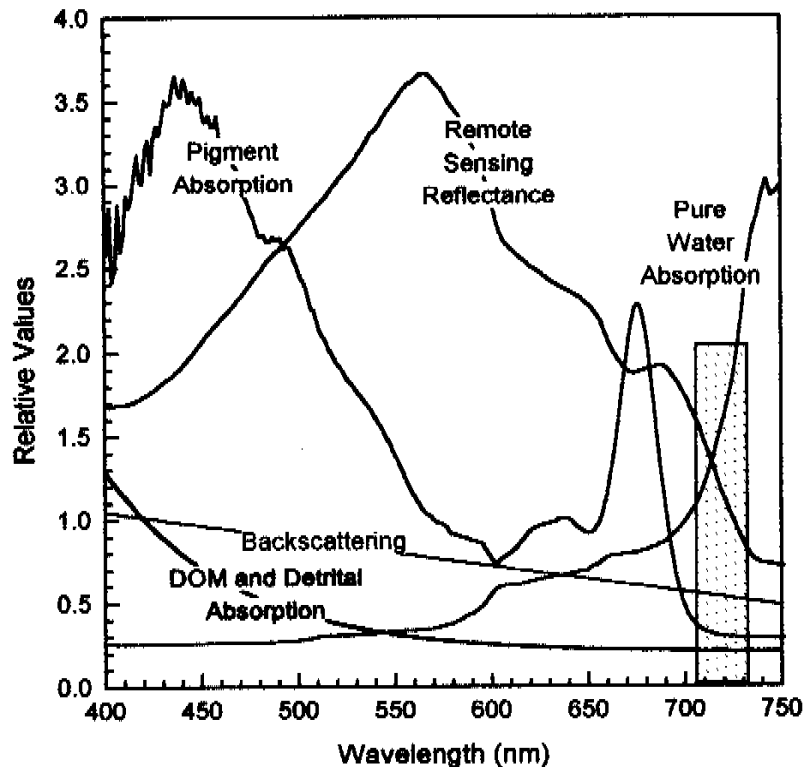


Figure 2. A representative coastal Rrs spectrum with relative curve shapes for component spectra.

RESULTS

A station from the Pear River in Mississippi is used to illustrate the surface correction and slope inversion algorithms. Figure 4 shows the uncorrected Rrs spectrum (black line), a "standard 2.1% Fresnel reflectance-corrected spectrum (red line), an AC9-corrected spectrum (the new surface correction algorithm, blue line), and a subsurface spectrum collected with a submersible fiber-optic probe (green line). Note the close agreement between the subsurface Rrs spectrum and the Rrs spectrum with the new surface correction applied.

The absorption/scattering slope algorithm was applied to the *in situ* reflectance data from the Pearl River station, and the results are compared with filter pad and AC9-measured values from the same station (Figure 5, absorption results). The red line labeled "Rrs Model" represents the results of the inversion model applied to the corrected, above-water Rrs measurements. The blue "Filter Pad" line represents the sum of particulate, DOM, and pure water absorption values from the filter pad measurements.

The green points are corresponding surface AC9 measurements. The modeled curve is in close agreement with both sets of measured values. Comparisons and error analyses are underway for the remaining stations.

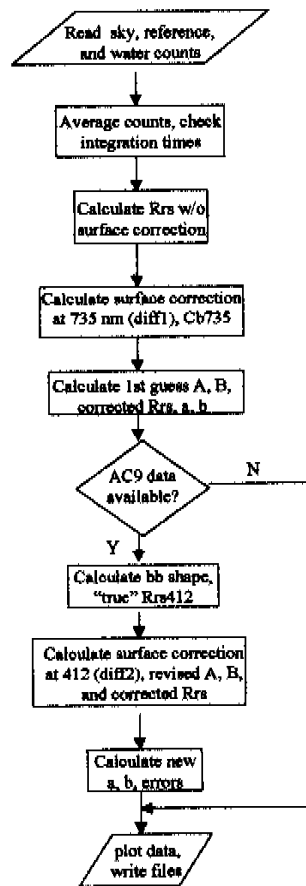


Figure 3. Summary of processing flow.

DISCUSSION AND CONCLUSION

The inversion algorithm presented here is based on a reflectance difference in the near-IR region of the spectrum where the slope of the reflectance spectrum is strongly related to the backscattering signal. Whereas, other inversion algorithms require measurements or estimates of the phytoplankton absorption spectrum^{6,7,8}, a highly complex and variable curve, this algorithm only requires a much simpler linear b_b curve shape.

We present an algorithm to correct above-water Rrs measurements for surface reflectance. The technique does not require subsurface Rrs measurements or polarized Rrs measurements. However, the correction is improved if measurements of total absorption at 412 nm are available, as well as a measurement or estimate of the "shape" of the spectral scattering relationship. Spectral above-water Rrs measurements corrected

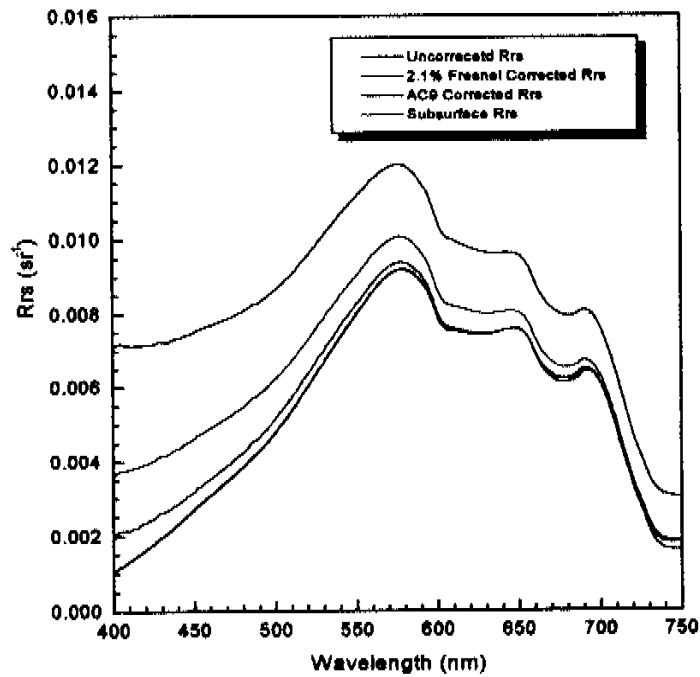


Figure 4. Corrected and uncorrected Rrs spectra. The blue line represents the new surface correction.

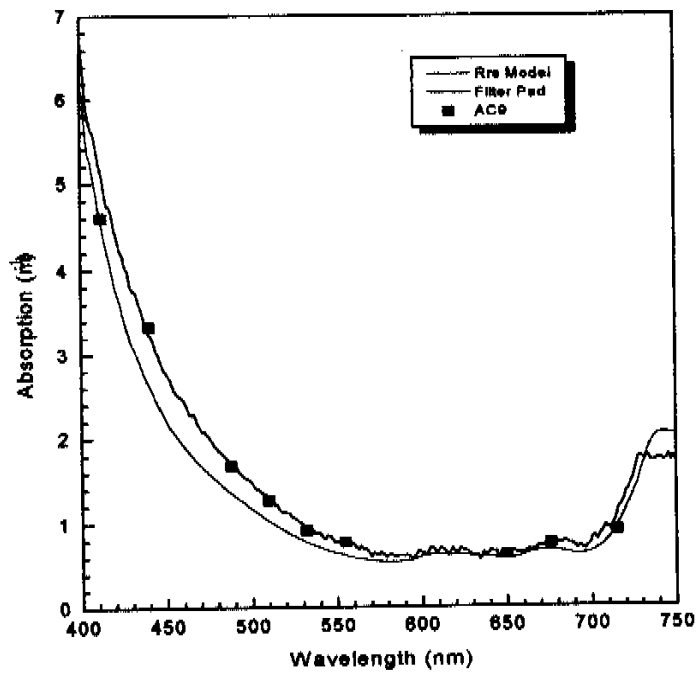


Figure 5. Measured vs. modeled absorption spectra. The red line represents the new inversion algorithm.

for sunglint and surface-reflected sky/cloud light agreed closely with the "true" in-water R_{rs} values if *in situ* measurements were used to adjust required curve shapes. The corrected R_{rs} spectra were incorporated into a new inversion algorithm to estimate spectral absorption and scattering, from the reflectance difference in the 715 – 735 nm wavelength region. We are currently testing the algorithms using data from thirteen experiments at five U.S. coastal locations collected over a two year period and representing a variety of absorption and scattering regimes. Preliminary results indicate that measured and modeled absorption and scattering coefficients agree favorably in both magnitude and spectral shape.

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