Retrieval of Remote Radiance Reflection Coefficients of Coastal Waters from the Inherent Optical Properties

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Retrieval of Remote Radiance Reflection Coefficients of Coastal Waters from the Inherent Optical Properties

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Abstract — Upwelling spectral radiances from the water surface and in situ inherent optical properties are measured concurrently at the same locations. Values of spectral radiance reflectance coefficients are derived from in situ data and compared with those obtained from spectral radiance data. An algorithm for estimating reflectance coefficients based on attenuation and absorption data is proposed and evaluated. This algorithm is based on the theoretically derived equations and the experimentally obtained regressions that connect scattering and backscattering coefficients. Overall comparison of derived and measured radiance coefficients shows that this algorithm is suitable for processing ground truth data for the purposes of calibration remote and in situ optical measurements.

INTRODUCTION

The results of the spectral measurements of radiance reflectance coefficient are compared with the results of the retrieval of these values from in situ measurements of inherent optical properties. These data are obtained simultaneously during the ground truth experiment near the West Florida coast in August 1994 (see Fig. 1). Upwelling spectral radiances from the water surface and in situ inherent optical properties are measured concurrently at the same locations. Values of spectral radiance reflectance coefficients are derived from in situ data and compared with those obtained from spectral radiance data. A model for estimating reflectance coefficients based on attenuation and absorption data is proposed and evaluated.

The measurement systems are: (a) spectral radiometer, with sensor bandwidth of 350-1000 nm and a one-degree acceptance angle (Analytical Spectral Devices, Inc. model FieldSpec™ VNIR); (b) nine-band beam absorption and attenuation meter (WET Labs, Inc. model A/C-9).

Data are collected at nine stations that range in depth from 2 meters to 23 meters. The spectral radiometer reflectance measurements are made at 30° from nadir and 180° azimuth from the sun. The examples of relative measurements are shown in Fig. 2. The vertical profiles of inherent optical properties are collected with the submersible A/C-9 beam transmissometer. The absorption and attenuation coefficients (see Figs. 3) are collected at nine stations transecting perpendicularly from the shoreline.

APPROACH

The experimental values of radiance reflection coefficient \( \rho_{\text{mes}} \) were calculated from three relative measurements of the sea \( N_{\text{sea}} \), sky \( N_{\text{sky}} \), and gray reference reflector \( N_{\text{ref}} \):

\[
\rho_{\text{mes}} = \left[ A_{\text{ref}} \left( N_{\text{sea}} - R_{\text{f}} N_{\text{sky}} \right) \right] / \left( \pi N_{\text{ref}} \right),
\]

Here \( A_{\text{ref}} \) is the reference albedo, and \( R_{\text{f}} \) is the Fresnel reflection coefficient of skylight [1]. Examples of measured radiancy coefficients \( \rho_{\text{mes}} \) are shown in Fig. 4.

The radiance reflection coefficients \( \rho_{\text{es}} \) derived from the \( a \) and \( b \) profiles are calculated according to the equation:

\[
\rho_{\text{es}} = T_{d} T_{u} R = \left( 1 - R_{d} \right) / n_{s}^{2}, \quad R = R_{t},
\]

here \( T_{d} \) and \( T_{u} \) are, respectively, downward and upward transmission coefficients of the sea surface, \( n_{s} \) is the water refractive index, and \( R \) is the diffuse reflectance of the water mass including effects of reflection from the bottom. The diffuse reflectance of a stratified \( n \)-layered shallow water was computed using the following iteration formula:

\[
R_{t} = \frac{R_{0}^{c} \left( 1 - R_{0}^{b} R_{n+1} \right) + \left( 1 - R_{0}^{c} R_{n+1} \right) \exp \left[ -v_{a} \left( z_{n+1} - z_{a} \right) \right]}{\left( 1 - R_{0}^{c} R_{n+1} \right) + \left( R_{0}^{c} R_{n+1} - R_{0}^{c} \right) \left[ -v_{a} \left( z_{n+1} - z_{a} \right) \right]},
\]

\[
R_{n+1} = A_{g} z_{a+1} = z_{b},
\]

Here \( A_{g} \) is the bottom albedo and \( z_{b} \) is the sea depth. All other parameters are inherent optical properties of the \( n \)-th layer calculated through the absorption and scattering profiles (see Figs. 3) measured during the experiment.

\[
v_{a} = 2 \alpha_{a} \frac{2(x_{a} - R_{0}^{c}) - \mu_{a} x_{a}}{(1 - x_{a}) R_{0}^{c}},
\]

\[
R_{0}^{n} = \left( \frac{1 - \mu_{a}}{1 + \mu_{a}} \right)^{2}, \quad R_{0}^{b} = \frac{2 - \mu_{a}}{2 - \mu_{b}} R_{0}^{n}, \quad \mu_{n} = \eta_{n} (2.6178398 + \eta_{n} (9.0040600 + \eta_{n} (14.83909 + \eta_{n} (8.817954 + 1.8593222 \eta_{n})))) \quad \eta_{n} = \sqrt{1 - \omega_{a}^{n}}, \quad \omega_{a}^{n} = \frac{a_{n}}{a_{n} + b_{n}}, \quad x_{a} = \frac{(1 - \mu_{a}^{2})^{2}}{1 + \mu_{a}^{2}} (4 - \mu_{a}^{2}), \quad b_{a} = \frac{x_{a} a_{n}}{1 - x_{a}}
\]

Equations (3)-(5), and (7) are based on the theory presented in Refs. [2]-[3]. The empirical Eqn. (6) is derived by the author from the experimental and in situ results published by Timofeyeva [4]. All values in Eqs. (6)-(7) with the subscript \( n \) are referred to the \( n \)-th layer. They are as follows: \( a_{n} \) is the absorption coefficient, \( x_{a} \) is the Gordon’s parameter, \( b_{n} \) is the scattering coefficient, \( \mu_{a} \) is an average cosine, \( \omega_{a}^{n} \) is the single-scattering albedo, and \( b_{a}^{n} \) is the backscattering coefficient.
Fig. 1. The image of the investigation area obtained from an aircraft. The center of the optical channel is located near 510 nm. The white elongated spot near the right black border of the sea image is a research vessel.

Fig. 3a. Experimental values of the absorption coefficient measured August 8, 1994, in the area shown in Fig. 1.

Fig. 2. Examples of the sea and the sky spectral radiances (in relative units) measured from the vessel in the area shown in Fig. 1.

Fig. 3b. Experimental values of the scattering coefficient measured August 8, 1994, in the area shown in Fig. 1.
Fig. 4. Examples of the restored with Eqn. (1) radiance coefficients $\rho_{ep}$ for different shallow water stations near the West Florida coast.

Figure 5 shows the comparison of the measured and restored radiance reflection coefficients. The overall error of restoration of the spectral radiance reflection coefficients with the algorithm presented above does not exceed 20% for our experiment.

CONCLUSION

The results of the spectral measurements of the radiance reflectance coefficient measured remotely from a small ship are compared with the results of the retrieval of this values through the in situ measured profiles of absorption and scattering coefficients obtained simultaneously during the ground truth experiment near the West Florida coast.

The presented algorithm for retrieval of the radiance coefficient using observed depth profiles of absorption and scattering coefficients is stable. The derived values, in the worst cases, have error less than 20%. The overall comparison of the derived and measured radiance coefficients shows that this algorithm is suitable for the calibration remote data using in situ observations.

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