Collaborative Investigations of Shallow Water Optics Problems

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LONG-TERM GOAL

The overall goal of this work is to understand in detail the relative contributions of water column optical properties, bottom morphology, bottom material reflectances, bottom bidirectional reflectance distribution functions (BRDFs), and external environmental conditions on remote-sensing reflectances in optically shallow waters.

OBJECTIVES

Various methodologies are now under development for the extraction of environmental information such as water-column absorption and scattering properties, bottom depth, and bottom type from remotely sensed hyperspectral imagery obtained in optically shallow waters. Regardless of the methodology used, errors in measured or predicted hyperspectral remote-sensing reflectances $R_{rs}(\lambda)$ will degrade our ability to extract information from the spectra. The potential errors therefore must be understood.

A "look-up-table" (LUT) methodology for extraction of environmental information from measured R_{rs} spectra is under development with separate funding (see annual report OP43 by C. D. Mobley). That technique relies on matching computed and measured R_{rs} spectra. To assess the potential errors in the spectrum matching, and to ascertain where additional effort should be expended in improving the underlying LUT databases, it is necessary to know when and how each potential source of error in computed R_{rs} spectra comes in to play.

APPROACH

I am using a combination of Hydrolight (www.hydrolight.info; Mobley and Sundman, 2001a,b) and Monte Carlo numerical modeling to quantify how various sources of error influence predicted R_{rs} spectra. For example, one can expect that water-column absorption and scattering properties (including phase function effects) will be less (more) important for shallow (deep) waters, and that bottom properties (BRDF, material reflectance) will be more (less) important in shallow (deep) waters. However, the interplay of these error sources is complex and simple rules for error analysis are hard to develop. Detailed numerical simulations and validation with observational data are needed for full understanding.

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14. ABSTRACT
The overall goal of this work is to understand in detail the relative contributions of water column optical properties, bottom morphology, bottom material reflectances, bottom bidirectional reflectance distribution functions (BRDFs), and external environmental conditions on remote-sensing reflectances in optically shallow waters.

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WORK COMPLETED

The first source of error in computed R_{rs} spectra that I have investigated is the effect of small-scale bottom morphology such as sand ripples on the effective bottom irradiance reflectance and on the BRDF. Zaneveld and Boss (2003) did an analytical study of sub-pixel ripples on the effective bottom reflectance. However, their study ignored multiple scattering between adjacent ripples and is thus exact only in the limit of a black bottom. For typical sediments such as sand, bottom material reflectances fall in the range of 0.2 to 0.7, and multiple scattering cannot be ignored. Zaneveld and Boss (2003) did not investigate ripple effects on the BRDF itself.

I have also selected several points in a PHILLS image of Adderly Cut, near Lee Stocking Island, Bahamas, where I am now doing a detailed closure study between predicted and measured hyperspectral R_{rs} spectra. These points have acoustic bathymetry and diver-observations of bottom type available for input to my numerical models and for validation of LUT retrievals based on PHILLS imagery.

RESULTS

I used my Backward Monte Carlo 3D (BMC3D; Mobley and Sundman, 2003) numerical model to study the effects of bottom ripples on the effective bottom reflectance and BRDF, for ripples much smaller than the pixel size of the viewing instrument. Figure 1 illustrates multiple scattering between bottom ripples. Figure 2 shows how the ripples affect the upwelling radiance (in the nadir-viewing direction) as a function of ripple amplitude (A_r) to wavelength (Λ_r) ratio and reflectance of the bottom material. In these simulations, the bottom material itself was assumed to be a Lambertian reflector with a material reflectance of R_b. Figure 2 thus shows that bottom roughness can significantly reduce the effective reflectance of the bottom, compared to the reflectance of the bottom material itself.

Zaneveld and Boss (2003) developed a simple formula for the ripple effect on the effective reflectance. Their formula says that the effective reflectance R_{eff} is simply the material reflectance R_b times the average cosine of the angle between the bottom normal and the normal to a level bottom (denoted by $<\cos>$), i.e. $R_{eff} = <\cos>R_b$. The dashed line in Fig. 2 shows that the Zaneveld and Boss (2003) $<\cos>$ formula for the effective bottom reflectance is correct only for single scattering between ripples, which is a good approximation only for dark sediments with a material reflectance of less than 0.1. I have found that the formula $R_{eff} = <\cos>R_b + (1 - <\cos>)R_b^2$ is able to predict R_{eff} and the nadir-viewing radiance to within three percent of the exact (BMC3D-computed) values for all material reflectance values and ripple amplitude-to-wavelength ratios less than 0.2, which is the approximate limit for sand ripples in nature.

However, 3D numerical simulation must be done to account for the ripple effects on the reflected radiance in off-nadir viewing directions. Figure 3 shows how the bottom-reflected radiance becomes increasingly non-isotropic as the incident radiance direction becomes more oblique to the mean bottom surface. That is to say, the effective bottom BRDF becomes increasingly non-Lambertian for more oblique incident directions, even if the material BRDF is Lambertian. The physics here is simple: one is seeing either the "sunny" or "shady" sides of the ripples, which corresponds to a non-Lambertian BRDF.
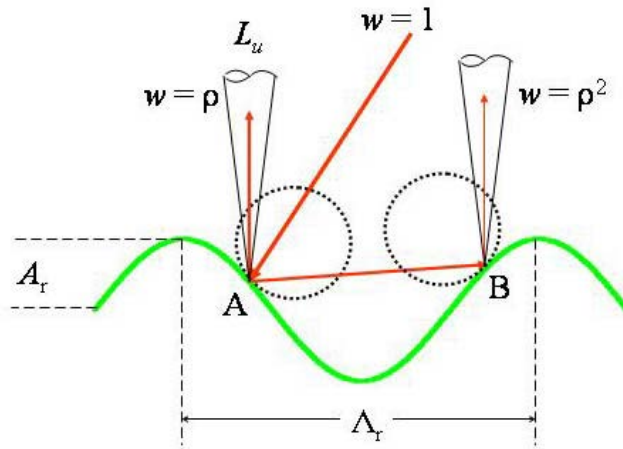
Figure 1. Illustration of multiple scattering between bottom ripples. Point A contributes to the nadir-viewing radiance by single scattering, and point B contributes by second-order scattering. ρ is the reflectivity of the bottom material and w is the energy contained in a packet of photons.
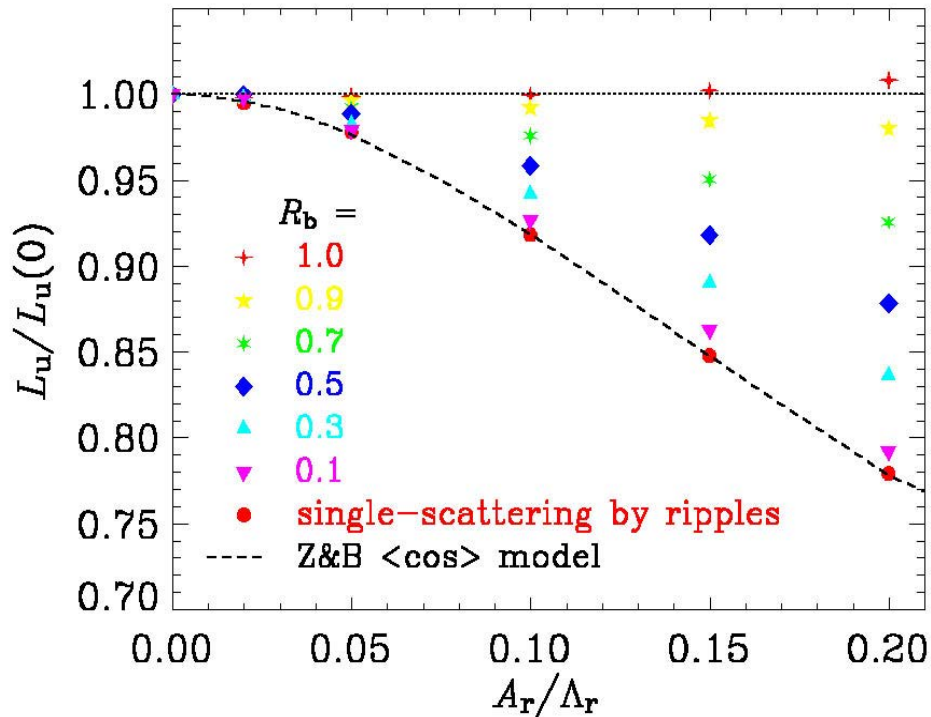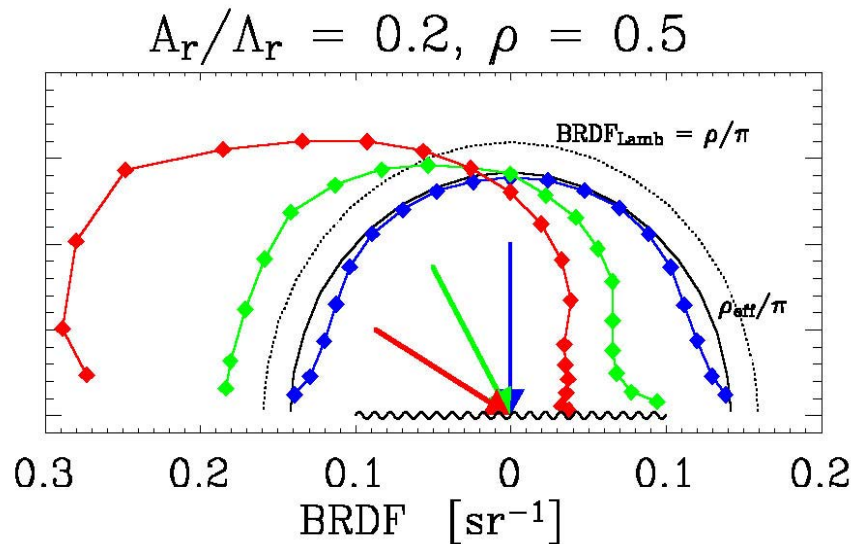

Figure 2. The nadir-viewing radiance L_u as affected by ripple geometry and material reflectance. L_u values are normalized to the value they would have if the bottom were smooth (no ripples). Note that there is no bottom morphology effect if the bottom is white (reflectance $R_b = 1$).

$$A_r / \Lambda_r = 0.2, \ \rho = 0.5$$

Figure 3. Cross sections of the BRDF in the plane of the incident radiance for normal incidence (blue), 30 deg incidence (green), and 60 deg incidence (red), for typical sand ripples with a material reflectance of 0.5.

Figure 4 shows the particular locations in Adderly Cut, Bahamas where I am now performing detailed closure studies between modeled and PHILLS-measured hyperspectral signatures. These points were chosen because they span the widest possible range of water depths (0 to 11 m) and bottom types (sand, sea grasses, corals) found in this image. Figure 5 shows two examples of predicted (by Hydrolight, red lines) and measured (by PHILLS, green lines) remote sensing reflectance spectra. The top pair of curves is for point 7 in Fig.4, which is a sand bottom with biofilm at 3.0 m depth; the bottom pair of curves is for point 2 in Fig. 4, which is a dark bottom of dense sea grass at 3.25 m depth. The excellent comparison of predicted and measured values is obvious. Error analysis of these spectra is underway.
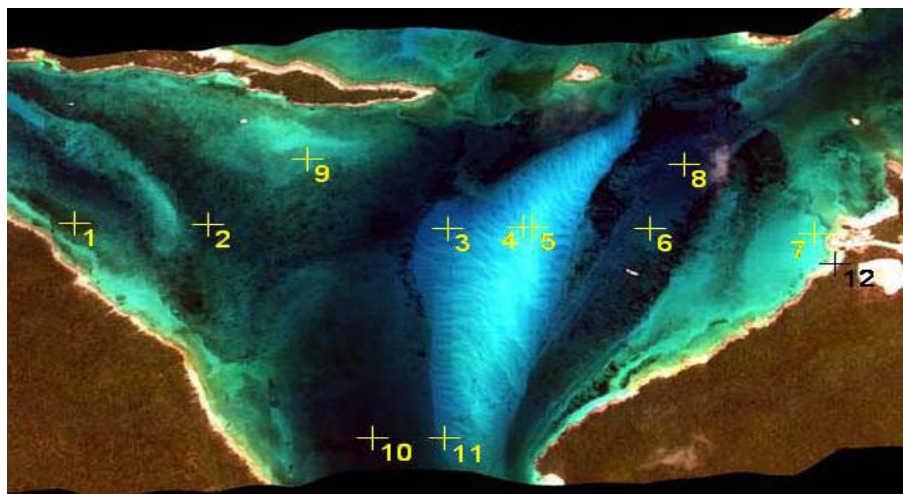
Figure 4. PHILLS image of the Adderly Cut area near Lee Stocking Island, Bahamas. The numbered points are the pixels where I am performing detailed closure calculations to evaluate the various sources of error in computed remote-sensing reflectances.
[the picture shows various sand shoals, sea grass beds, and coral reefs]

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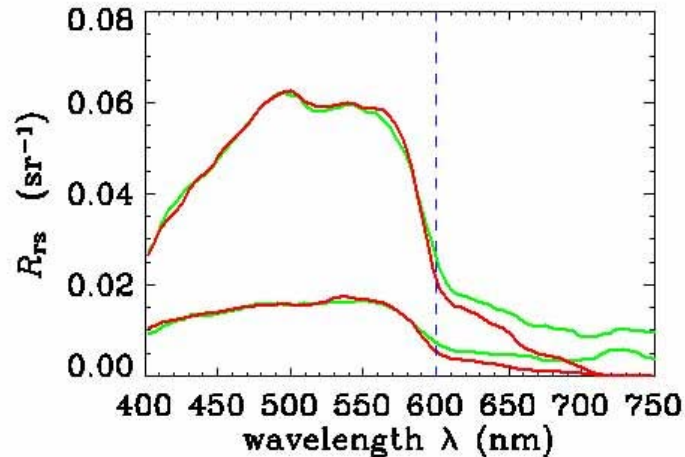
Figure 5. Comparison of PHILLS (green lines) and Hydrolight-predicted (red lines) hyperspectral remote-sensing reflectances $R_{rs}(\lambda)$ for point 2 in Fig. 4 (bottom lines, sea grass bottom) and point 7 (sand bottom).

IMPACT/APPLICATION

Hyperspectral imagery is increasingly used for a wide range of problems from mapping and monitoring seagrass beds and coral reefs to remote sensing of bathymetry and bottom classification for military applications. For quantitative analysis of hyperspectral imagery it is necessary to have calibrated, accurate hyperspectral reflectance spectra. This need in turn makes it necessary to evaluate in detail the various sources of error in such spectra. By quantifying various error sources, this work will also provide guidance as to where additional effort should be expended to improve measurements and models used in the analysis of hyperspectral data.

RELATED PROJECTS

This work uses data sets, imagery, and models (viz., BMC3D) previously obtained or developed during the ONR CoBOP program. This work directly contributes to my separately funded work on developing the look-up-table methodology for extraction of environmental information from hyperspectral imagery (annual report OP43).

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HONORS/AWARDS/PRIZES

C. D. Mobley of Sequoia Scientific, Inc. was invited to give the prestigious Riley Memorial Lecture at Dalhousie University (www.dal.ca/~wwwocean/ocean_1093.html) in September 2003. This honor is conferred each year on a scientist of international reputation by the Oceanography Dept. of Dalhousie University, Halifax, NS, Canada. Mobley discussed some of the spectrum analysis work in his Riley lecture, and the BRDF simulation work was presented in a separate seminar delivered to the Dalhousie Oceanography Department.