Radiative Transfer Modeling for CoBOP

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Award Number: N0001497C0018
http://www.onr.navy.mil/sci_tech/ocean/onrpgahk.htm

LONG-TERM GOAL

The overall goal of this work is to take oceanic radiative transfer theory into a new domain: optically shallow waters with spatially variable bottom optical properties, including sloping bottoms and non-Lambertian bottom bidirectional reflectance distribution functions.

OBJECTIVES

Currently available models for analysis of hyperspectral remote sensing imagery in shallow waters almost always assume that the bottom is a level, homogeneous, Lambertian reflecting surface—a spatially homogeneous surface at a constant depth whose reflected radiance appears the same from all viewing directions. The first objective of this year's work was to quantify the extent to which non-Lambertian bottoms can affect upwelling radiances as would be detected by above-water sensors. Many studies of marine light fields also assume the water and bottom optical properties to be horizontally homogeneous, which is not the case in shallow waters with patchy or sloping bottoms. The second objective this year was to quantify the extent to which patchy or sloping bottoms influence the water-leaving radiance. In particular, I wished to see when a 1-D (horizontally homogeneous, constant depth) radiative transfer model is sufficient, and when a computationally expensive 3-D Monte Carlo model must be used.

APPROACH

The Hydrolight radiative transfer model (http://www.sequoiasci.com; Mobley and Sundman, 2001a,b) allows for non-Lambertian bottom boundaries. However, because of the lack of measured bidirectional reflectance distribution functions (BRDFs; Mobley, Zhang, and Voss, 2001; Zhang et al., 2001) for actual ocean bottom materials, Hydrolight's mathematical capability had not been previously exploited. This year, non-Lambertian BRDFs were used in Hydrolight to simulate the effects of horizontally uniform but non-Lambertian bottoms on in-water and water-leaving radiances.

The Hydrolight model requires the water and the surface and bottom boundaries to be horizontally homogeneous; Hydrolight is therefore not applicable to shallow waters with spatially variable or sloping bottoms. To simulate the inherently 3-D light fields due to the effects of spatially variable or sloping bottoms, Monte Carlo models must be used.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Radiative Transfer Modeling for CoBOP**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Sequoia Scientific, Inc.,Westpark Technical Center,,15317 NE 90th Street,Redmond,,WA, 98052**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The overall goal of this work is to take oceanic radiative transfer theory into a new domain: optically shallow waters with spatially variable bottom optical properties, including sloping bottoms and non-Lambertian bottom bidirectional reflectance distribution functions.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

This last year of CoBOP work was used to conclude the model development and studies begun in earlier years, and to prepare and submit papers on that work. In particular, non-Lambertian BRDFs were used to simulate radiances for situations of interest to the airborne Portable Hyperspectral Imaging Low-Light Spectrometer (PHILLS) system, which played a major role in the CoBOP field programs (Davis et al., 1999). BRDFs as measured by K. Voss for ooid sand and grapestone were used for simulations of bare substrates, and various analytical BRDFs developed for terrestrial plant canopies were used a proxies for seagrass BRDFs, which were not measured in the CoBOP field experiments.

A Backward Monte Carlo model was developed to simulate 3-D radiance distributions caused by spatially variable bottom reflectances (such as patchy sand and seagrass bottoms) and by sloping or rippled bottoms. The mathematical techniques are described in Gordon (1985), Mobley (1994, Section 6.2), and Mobley and Sundman (2001c). This model, called BMC3D, allows the user to specify an arbitrary spatial pattern of bottom BRDFs (which can be non-Lambertian) as well as sensor location, viewing direction, and field of view.

Results of my work are described in three papers that have been submitted to the CoBOP special issue of *Limnology and Oceanography* (Mobley, Zhang, and Voss, 2001; Mobley and Sundman, 2001c; Voss et al., 2001). In addition to the work explicitly described here, I authored or co-authored three other papers (Hoge et al., 2000; Leathers et al., 2001; Mobley, Sundman, and Boss, 2001) and three book chapters (Bissett et al., 2001; Mobley 2001a,b) that contribute to the overall goals of CoBOP or to other Navy needs; three papers were presented at Ocean Optics XV.

RESULTS

Figure 1 (from Mobley, Zhang, and Voss, 2001) shows an example of Hydrolight simulations of the errors that occur in predictions of the water-leaving radiance L_w (the quantity of interest in remote sensing) if a non-Lambertian bottom is replaced by a Lambertian bottom *having the same irradiance reflectance R.* The non-Lambertian bottoms referenced in this figure include a measured BRDF of ooid sand at the CoBOP field site, an analytical BRDF with parameters chosen to simulate sand (Hapke, 1993, Eq. 8.89), and semianalytical BRDFs of a wheat field and coniferous forest (Rahman, *et al.*, 1993), which were used as proxies for a seagrass BRDF, the exact form of which is unknown. The water-column optical properties were taken from measured values at the CoBOP Bahamas site. To accentuate the bottom effects, the water was only 1 m deep and the sun was at 50 deg from the zenith. These errors thus represent a worse-case situation of very shallow water and large solar angle. The errors become smaller as the bottom becomes deeper or the sun approaches the zenith. θ_v and ϕ_v are the polar and azimuthal viewing directions, respectively. The viewing directions seen in a PHILLS scan are shown in green. The sun was located at $(\theta_v, \phi_v) = (50°,180°)$.

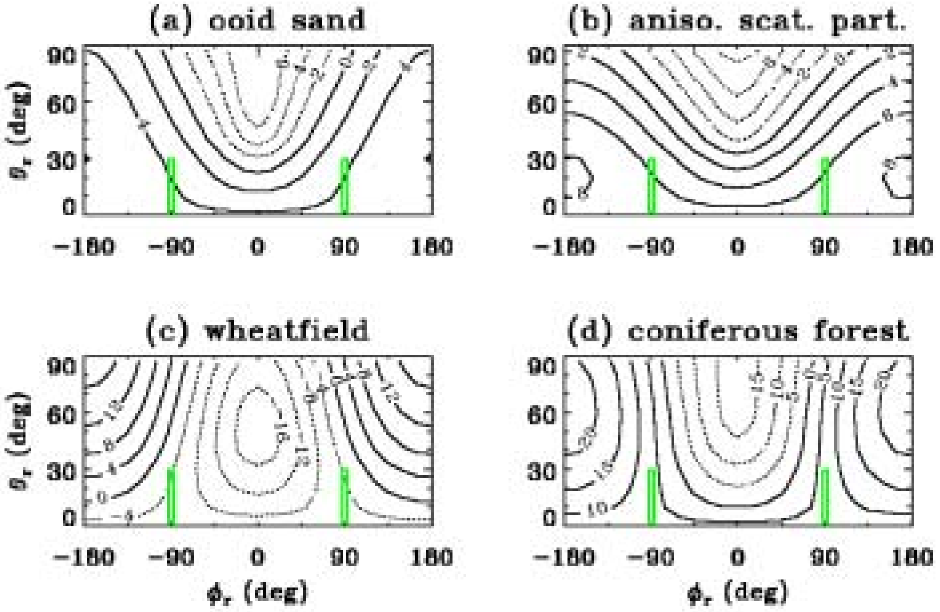

Fig. 1. Contours show the percent errors in water-leaving radiance that result from replacing a non-Lambertian BRDF with a Lambertian BRDF having the same irradiance reflectance. Green boxes show the PHILLS viewing directions. [For directions relevant to remote sensing, the errors are less than 10%]

Simulations like those of Fig. 1 yield the first important conclusion of my work:

> For solar and viewing directions relevant to most ocean-color remote sensing, a non-Lambertian bottom can be modeled as a Lambertian bottom *having the same irradiance reflectance* $R = E_u/E_d$, with errors of less than 10% in L_w.

Thus the different *angular* bottom reflectance patterns do not make much difference in the signals received by the PHILLS sensor. *The crucial measurement that optically describes a bottom type is the irradiance reflectance.*

Figure 2 (from Mobley and Sundman, 2001c) shows a BMC3D simulation of the upwelling irradiance E_u at the surface, as would result from moving an irradiance sensor across a boundary between bottom types having $R = 0.05$ (e.g., seagrass) and $R = 0.5$ (e.g., bright sand). E_u is sometimes used in remote sensing studies because it is easily measured and can be related to the upwelling radiance. The bottom was at a depth of 5 m, and the water IOPs were the same as used for Fig. 1. The green lines in the figure show the Hydrolight-computed values for infinite grass and infinite sand bottoms for comparison. The blue line shows E_u as computed by BMC3D. In this simulation, the instrument begins “seeing” the boundary at a horizontal distance of roughly twice the water depth. The red line shows E_u computed using the simple 1D model of Eqs. (1) and (2) below.

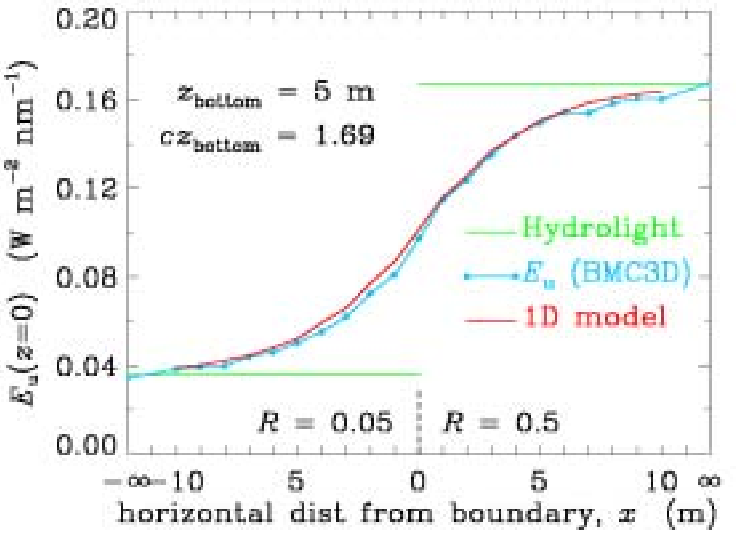

Fig. 2. E_u as a function of horizontal position near a boundary between bottoms of different reflectances.

In Fig. 2, the exact (to within statistical noise) BMC3D calculations required hours of computer time; the Hydrolight calculations took less than 5 seconds. It would therefore be computationally desirable to have an approximate model that could use the Hydrolight 1D solutions for the two different bottoms in combination with the sensor viewing geometry to predict E_u (or other quantities) near such boundaries. Such a 1D model was developed from simple radiative transfer approximations. The model, when applied to the situation seen in Figs. 2 and 3, has the form

$$E_u(x) = w(x;1)\, E_u(1D;1) + w(x;2)\, E_u(1D;2)\,, \qquad (1)$$

where

$$= \frac{\int_{\Xi} \quad - \quad \theta \quad \theta \quad \Omega}{\int_{\Xi} \quad - \quad \theta \quad \theta \quad \Omega} \qquad (2)$$

In Eqs. (1) and (2), $E_u(1D;i)$ is the 1D (Hydrolight) solution for bottom type i, $S(\theta)$ is the sensor response function [$S(\theta) = \cos\theta$ for a measurement of E_u], c is the beam attenuation of the water, and the integration over $\Xi(i)$ means "integrate over the directions where the sensor at location x sees bottom type i." As seen in Fig. 2, the simple 1D model of Eqs. (1) and (2) gives rather good predictions of the 3D situation; in this simulation, the difference between the 1D model and the exact 3D calculation was less than 10%. Additional simulations such as this yield the second important conclusion of this work:

> Using a 1D radiative transfer model such as Hydrolight to predict E_u or L_u can give errors of many tens of percent near the boundary of highly contrasting bottom types. However, a simple analytical model that weights the 1D solutions according to the sensor response and location can reduce these errors to roughly 10%.

A similar statement can be made about sloping bottoms, in which case a sloping bottom can be modeled as a level bottom using Hydrolight with a correction for the change in the incident angle of the sun’s unscattered beam onto the bottom.

IMPACT/APPLICATION

Inverse models are being developed by other ONR investigators to retrieve bottom depths and bottom classification information from hyperspectral ocean color sensors such as PHILLS. Those retrieval algorithms generally assume the bottom to be a level, Lambertian reflector. Radiative transfer simulations like those shown here allow the proposed inversion algorithms to be evaluated for patchy, sloping, non-Lambertian bottom boundaries.

The 3-D vs. 1-D simulations allow a determination of when a computationally efficient 1-D model like Hydrolight can be used to simulate the ocean optical environment, and when a much more expensive 3-D Monte Carlo model must be run. The BMC3D model developed here also allows for simulations of particular sensor geometries (such as sensor angular response), which cannot be exactly simulated in models such as Hydrolight.

TRANSITIONS

1. The BMC3D code was transitioned to Dr. Curtiss Davis of NRL Code 7212 for use in computing the effects of instrument self-shading on the buoyed sensors, which are used to acquire sea-truth data for evaluation of hyperspectral ocean-color remote sensing systems. Those results are described in Leathers et al. (2001).

2. The BMC3D code was transitioned to Dr. Vladimir Haltrin of NRL Code 7331 for use in various simulations of underwater 3D light fields.

3. The BMC3D code was used by Mr. Richard Tompkins of the Office of Naval Intelligence (ONI-241) to simulate the visibility of underwater objects.

4. The BMC3D code is being used by Todd Bowers at the Stennis Space Center to analyze underwater visibility data.

RELATED PROJECTS

Measurements of BRDFs for various bottom types were made by K. Voss (Zhang et al., 2001), and measurements of water and bottom optical properties and associated light fields were made by various investigators in the CoBOP program. Their data were used in conjunction with my models to evaluate the results of the optical closure experiment conducted during the 2000 field experiment (Voss et al., 2001).

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