A Hybrid Modular Optical Model To Predict 2-D and 3-D Environments in Ports and Beneath Ship Hulls for AUV Sensor-Performance Optimization in MCM Activities

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LONG-TERM GOALS

The long-term goal of this research effort is to develop a method to predict rapidly the visible radiance distribution in complex three-dimensional marine environments as found in ports and anchorages. Effective deployment of AUV- or ROV-mounted sensors to inspect ship hulls and port facilities will depend on accurate, real-time prediction of the sub-surface optical environment at the time and place of inspection.

OBJECTIVES

The initial objective of this work is to develop the model system for two-dimensional environments. The model concept involves four distinct phases: 1) Modeling the optical response of individual two-dimensional elements using Monte Carlo techniques, analytic expressions, and ad-hoc definitions; 2) Building the two-dimensional region to be modeled by combining the elements developed in the previous phase; 3) Determining the radiance field around each element of the modeled environment by employing an iterative technique to diffuse the source radiance through-out the environment; 4) Displaying the results of the model numerically and graphically.

APPROACH

Consider a point, $\boldsymbol{\rho_i}$, on the surface of an arbitrary region (Fig. 1).

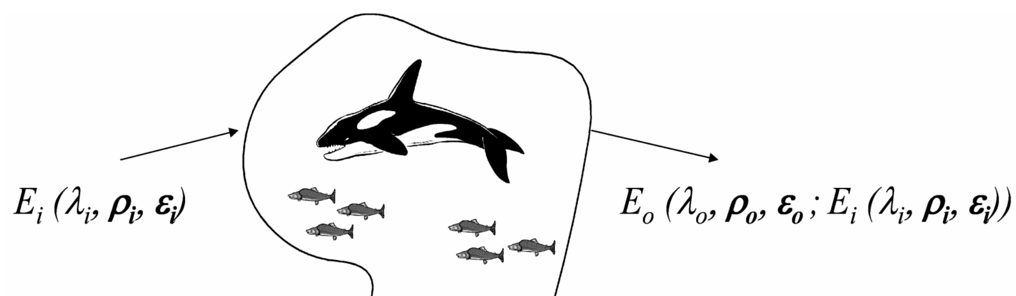

Figure 1:** $E_o(\lambda_o,\rho_o,\varepsilon_o;E_i(\lambda_i,\rho_i,\varepsilon_i))$ **is the part of the irradiance emitted from the region at wavelength** λ_o**, point** ρ_o**, and direction** ε_o **when the region is illuminated by irradiance incident at wavelength** λ_i**, point** ρ_i**, and direction** ε_i**.

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14. ABSTRACT
The long-term goal of this research effort is to develop a method to predict rapidly the visible radiance distribution in complex three-dimensional marine environments as found in ports and anchorages. Effective deployment of AUV- or ROV-mounted sensors to inspect ship hulls and port facilities will depend on accurate, real-time prediction of the sub-surface optical environment at the time and place of inspection.

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This point is being illuminated by a pencil of radiant power, E_i, at wavelength λ_i and from direction $\boldsymbol{\varepsilon_i}$. E_i is that portion of the irradiance at $\boldsymbol{\rho_i}$ that arrives from direction $\boldsymbol{\varepsilon_i}$, expressed in units W m^{-2} sr^{-1}. As a result of this illumination, power may be emitted from the region at wavelength λ_o, point $\boldsymbol{\rho_o}$, and direction $\boldsymbol{\varepsilon_o}$. In the following discussion we will omit for simplicity specific reference to wavelength dependence, and we also defer treatment of internal sources, as the extension of the technique to include these phenomena is straightforward. Surface reflectance, however, is included in the following formulation.

The linearity of the Radiative Transfer Equation (RTE) implies that $E_o(\boldsymbol{\rho_o},\boldsymbol{\varepsilon_o};E_i(\boldsymbol{\rho_i},\boldsymbol{\varepsilon_i}))$ is proportional to $E_i(\boldsymbol{\rho_i},\boldsymbol{\varepsilon_i})$. We denote the point-by-point constant of proportionality as the "response function" (RF), defined as

$$E_o(\boldsymbol{\rho_o},\boldsymbol{\varepsilon_o};E_i(\boldsymbol{\rho_i},\boldsymbol{\varepsilon_i})) \quad = \quad R(\boldsymbol{\rho_o},\boldsymbol{\varepsilon_o};\boldsymbol{\rho_i},\boldsymbol{\varepsilon_i})E_i(\boldsymbol{\rho_i},\boldsymbol{\varepsilon_i}). \tag{1}$$

Now, if R is known for all points on the boundary of the region, and for all directions, then the power emitted by the region is completely determined by the incident power distribution. The total power emitted from the differential of surface area centered on $\boldsymbol{\rho_o}$ and propagating within the differential cone of directions centered on $\boldsymbol{\varepsilon_o}$ is given by

$$E_o(\rho_o,\varepsilon_o)dA(\rho_o)d\Omega(\varepsilon_o) = \iint R(\rho_o,\varepsilon_o;\rho_i,\varepsilon_i)E_i(\rho_i,\varepsilon_i)\, dA\; d\Omega\,. \tag{2}$$

The integrals in (2) are over the entire boundary of the region and all directions, $d\boldsymbol{\Omega}$, which are incident on the region at $dA(\boldsymbol{\rho_o})$.

The relationships given in (1) and (2) are not very useful (except to Monte Carlo programmers), but do warrant two comments. First, R is a relationship between points on the surface of the region and is not explicitly dependent on the optical media within. Of course, R does depend on the material within the region. But if R can be measured, deduced, or defined for the region, then whenever the power distribution incident on the surface of the region is known the emitted power distribution can be calculated without further reference to the optical properties of the region. Secondly, there actually are regions for which R is known or may be defined exactly. These include regions within which no scattering takes place and boundary regions that have known reflectance characteristics.

The approach used in the preliminary stages of this work is to model two-dimensional elements such as infinitely long bars of square and right-triangular cross-section using Monte Carlo techniques. The air/sea interface, boundary surfaces, and the upper boundary representing the sky are modeled by infinitely long strips. The response functions of the strips are defined analytically.

Once a collection of response functions is developed to represent the characteristics of the environment to be modeled, the elemental bars and strips are arranged to approximate the geometry of the model environment.

Then, for each element in the model environment, the radiant input to the element from adjacent elements is determined, and the output state of the element is adjusted according to the element's response function. This process is repeated for all elements in the environment until the change in elemental output states is negligible. At this point the radiance field on the boundary of each element is known.

WORK COMPLETED

We have developed Monte Carlo programs to model the response functions of two-dimensional bars of square and prismatic cross-section. Horizontal two-dimensional strips representing the sky (light source), the air/sea interface, sea bottom have been defined. Other two-dimensional strips have been developed to represent the sides and bottoms of ships. We have also developed the computer code to combine the basic elements into regions of the environment to be modeled. The computer programs that "relax" the assembly of elements have been implemented and the radiance distributions of one-dimensional and two-dimensional environments have been modeled. One-dimensional results have been compared against the well-known Hydrolight[1] model.

RESULTS

Figure 2 shows the (normalized) downward irradiance beneath and adjacent to a barge afloat in relatively clear water. Note that the vertical and horizontal axes are plotted to different scales. Data for this plot were calculated at eighth-meter resolution, but smoothed to a spatial resolution of one meter for plotting. The vertical lines just below the bottom corners of the barge are contouring artifacts caused by the combination of this low spatial resolution and the high horizontal gradient of downward irradiance at the edges of the barge. The shadow that extends above the sea surface on the left side of the barge is shown clearly, as is the sharp horizontal gradient in downward irradiance at the lower right corner of the barge. The contours indicate that a submersible vehicle moving beneath the barge at a depth of four meters would encounter changes in downward irradiance of nearly three orders of magnitude. The downward irradiance diffuses beneath the barge to fill in the shadow, but the downward irradiance at the bottom in the deepest part of the barge shadow is more than an order of magnitude less than in the open spaces adjacent to the barge. Curvature of the downward irradiance contours extends to the edges of the plot, indicating that the downward irradiance in the open areas between the barges is perturbed by the presence of the barges and shadows.

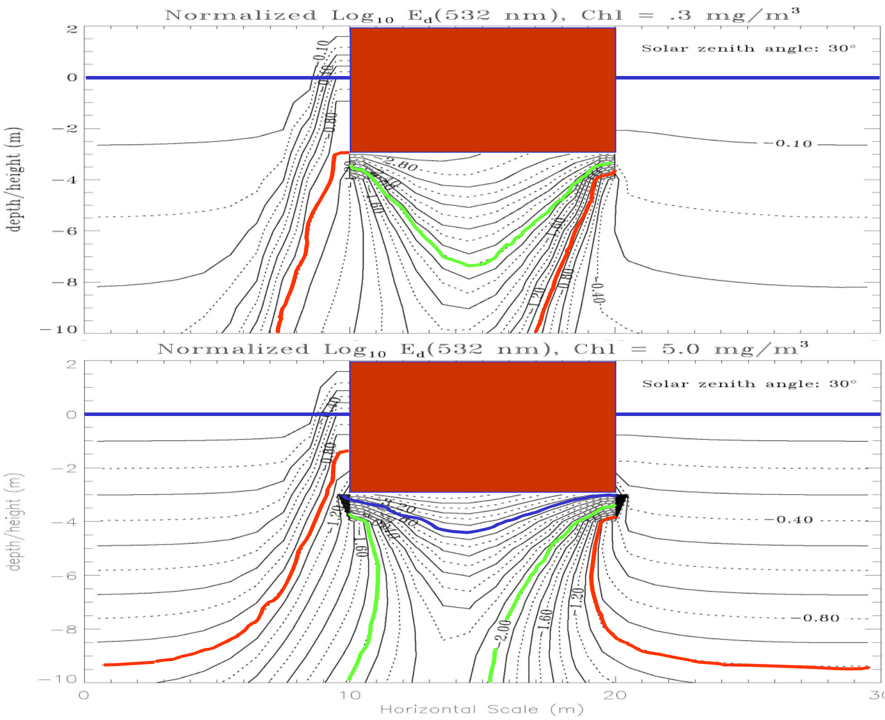

Figure 2: Normalized Log_{10} E_d(532 nm), Chl = 0.3 mg/m^3 as calculated by the hybrid model. Vertical and horizontal axes are not plotted to same scale.

IMPACT/APPLICATIONS

Effective deployment of instrument packages requires both the proper choice of instrument and an operational plan that allows the instrument to function most productively in the ambient optical environment. We believe that the hybrid modeling technique will allow us to compile a large database of solved model scenarios that represent typical environments in which security inspections will take place. As more model geometries and optical environments are required and solved, the database will grow. Access to this database will enable inspectors and equipment operators on site to assess the optical environment at the time of inspection, thus providing the information necessary to determine the optimal inspection strategy.

RELATED PROJECTS

This project has a close association with the ROBOT project (Kaltenbacher et al.). ROBOT is an AUV/ROV deployed, laser-line imaging system designed to produce 3-dimensional maps of underwater surfaces (bottoms, seawalls, hulls, etc.) We are utilizing our methodologies and hardware to quantify and predict performance parameters for both the on-line and fluorescence (see RESULTS) modes of operation of the ROBOT systems well as to develop algorithms for automatic (computerized) target recognition.

We are also calculating the structure of the underwater light field around objects (e.g. ship and seawall shadows) under various environmental conditions for comparison to field measurements acquired under Optical Variability and Bottom Classification in Turbid Waters: Phase III (ONR, Carder and Costello).

Finally, this project benefits from the database acquired during the ONR project Coastal Benthic Optical Properties (CoBOP, Carder and Costello) field campaigns.

REFERENCES

C. D. Mobley, *Hydrolight 4.0 User's Guide, Second Printing* (Sequoia Scientific, Inc., Redmond, Wash., 1998).

PUBLICATIONS

P. N. Reinersman and K. L. Carder, "Hybrid Numerical Method for Solution of the Radiative Transfer Equation in One, Two, or Three Dimensions", Appl. Opt. (to be published).

PATENTS

U.S. Provisional Patent entitled "Methods and Computer Program Products for Determining the Radiance Field of a Modeled Environment" (USF ref. No. 03B064PR) filed August 25, 2003. Reinersman and Carder.