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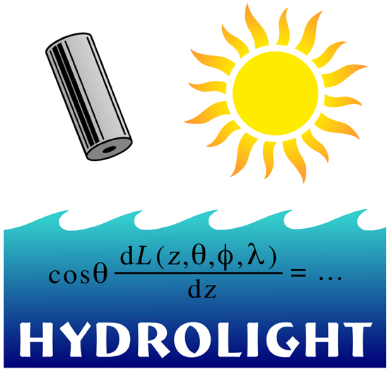

HYDROLIGHT 4.2

Knowledge of the radiance distribution within and leaving a water body is a prerequisite for the solution of many problems in ocean color remote sensing, biological primary productivity, mixed-layer thermodynamics, and underwater visibility. Moreover, because radiance is the fundamental radiometric quantity, all other quantities of interest to optical oceanographers, such as various irradiances, *K*-functions, and reflectances, can be computed once the radiance is known.

HYDROLIGHT is a radiative transfer numerical model that computes radiance distributions and derived quantities for natural water bodies. In brief, **HYDROLIGHT** solves the radiative transfer equation to compute the time-independent radiance distribution within and leaving any plane-parallel water body. The spectral radiance distribution is computed as a function of depth, direction, and wavelength within the water. The upwelling radiance just above the sea surface includes both the water-leaving radiance and that part of the incident direct and diffuse sky radiance that is reflected upward by the wind-blown sea surface. The water-leaving and reflected-sky radiances are computed separately in order to isolate the water-leaving radiance, which is the quantity of interest in most remote sensing applications. Input to the model consists of the absorbing and scattering properties of the water body, the nature of the wind-blown sea surface and of the bottom of the water column, and the sun and sky radiance incident on the sea surface. Output consists both of archival printout and of files of digital data, from which graphical, spreadsheet, or other analyses can be performed.

HYDROLIGHT is designed to solve a wide range of problems in optical oceanography and limnology. The input absorbing and scattering properties of the water body can vary arbitrarily with depth and wavelength. These inherent optical properties (IOPs) can be obtained from actual measurements or from analytical models, which can build up the IOPs from contributions by any number of components. The input sky radiance distribution can be completely arbitrary in the directional and wavelength distribution of the solar and diffuse sky light. In its most general solution mode, **HYDROLIGHT** includes the effects of inelastic scatter by chlorophyll fluorescence, by colored dissolved organic matter (CDOM) fluorescence, and by Raman scattering by the water itself. The model also can simulate internal layers of bioluminescing microorganisms.

HYDROLIGHT employs mathematically sophisticated invariant imbedding techniques to solve the radiative transfer equation. Details of this solution method are given in Mobley (1994, Chapter 8). When computing the full radiance distribution, invariant imbedding is computationally extremely fast compared to other solution methods such as discrete ordinates and Monte Carlo simulation. Computation time is almost independent of the depth variability of the inherent optical properties (whereas a discrete ordinates model, which resolves the depth structure as *N* homogeneous layers, takes *N* times as long to run for stratified water as for homogeneous water). Computation time depends linearly on the depth to which the radiance is desired (whereas Monte Carlo computation times increase exponentially with depth). All quantities are computed with equal accuracy, and there is no statistical noise in the results. Monte Carlo models suffer from statistical noise, and quantities such as radiance contain more statistical noise than quantities such as irradiance, because the simulated photons must be partitioned into more directional bins when computing radiances. The water-leaving radiance—the fundamental quantity in remote sensing studies—is very time consuming to compute with Monte Carlo simulations because so few incident photons are backscattered into upward directions. **HYDROLIGHT** version 3.0 was compared with Monte Carlo and discrete ordinates models in Mobley *et al.* (1993, wherein **HYDROLIGHT 3.0** is referred to as "Invariant Imbedding").

Ways in Which HYDROLIGHT Can Be Used

HYDROLIGHT has been used in a variety of studies ranging from bio-optical oceanography to remote sensing. Some of the ways in which **HYDROLIGHT** can be used are as follows:

- **HYDROLIGHT** can be run with modeled input values to generate in-water light fields, which in turn become the input to models of primary productivity or mixed-layer thermodynamics. Such information is fundamental to the coupling of physical, biological, and optical feedback models.

- **HYDROLIGHT** can be run with the IOP's of different water types to simulate in-water light fields for the purpose of selecting or designing instruments for use in various water types. Such information can aid in the planning of field experiments.

- **HYDROLIGHT** can be run with assumed water inherent optical properties as input, in order to obtain estimates of the signals that would be received by various types or configurations of remote sensors, when flown over different water bodies and under different environmental conditions. Such information can guide the planning of specific operations.

- **HYDROLIGHT** can be used to isolate and remove unwanted contributions to remotely sensed signatures. Consider the common remote-sensing problem of extracting information about a water body from a downward-looking imaging spectrometer. The detected radiance contains both the water-leaving radiance (the signal, which contains information about the water body itself) and sky radiance reflected upward by the sea surface (the noise). **HYDROLIGHT** separately computes each of these contributions to the radiance heading upward from the sea surface and thus provides the information necessary to correct the detected signature for surface-reflection effects.

- When analyzing experimental data, **HYDROLIGHT** can be run repeatedly with different water optical properties and boundary conditions, to see how particular features of the data are related to various physical processes or features in the water body, to substance concentrations, or to boundary or other external environmental effects. Such simulations can be valuable in formulating hypotheses about the causes of various features in the data.

- **HYDROLIGHT** can be used to simulate optical signatures for the purpose of evaluating proposed remote-sensing algorithms for their applicability to different environments or for examining the sensitivity of algorithms to simulated noise in the signature.

- **HYDROLIGHT** can be used to characterize the background environment in an image. When attempting to extract information about an object in the scene, all of the radiance from the natural environment may be considered noise, with the radiance from the object being the signal. The model can then be used to compute and remove the environmental contribution to the image.

- **HYDROLIGHT** can be run with historical (climatological) or modeled input data to provide estimates about the marine optical environment during times when remotely or in-situ sensed data are not available.

Output can be provided in many forms: water-leaving radiances for remote-sensing applications, in-water apparent optical properties (such as *K* functions) for Lidar bathymetry applications, or ambient light field data as may be relevant to underwater visibility or optical communications applications.

Input to HYDROLIGHT

In order to run **HYDROLIGHT** to predict the spectral radiance distribution within and leaving a particular body of water, during particular environmental (sky and surface wave) conditions, the user supplies the core model with the following information (via built-in submodels, or user-supplied subroutines or data files):

- **The inherent optical properties of the water body**. These optical properties are the absorption and scattering coefficients and the scattering phase function. These properties must be specified as functions of depth and wavelength.

- **The state of the wind-blown sea surface**. **HYDROLIGHT** models the sea surface using the Cox-Munk capillary wave slope statistics, which adequately describe the optical reflection and transmission properties of the sea surface for moderate wind speeds and solar angles away from the horizon. In this case, only the wind speed needs to be specified.

- **The sky spectral radiance distribution**. This radiance distribution (including background sky, clouds, and the sun) can be obtained from semi-empirical models that are built into **HYDROLIGHT**, from observation, or from a separate user-supplied atmospheric radiative transfer model (such as MODTRAN).

- **The nature of the bottom boundary**. The bottom boundary is specified via its bidirectional reflectance distribution function (BRDF). If the bottom is a Lambertian reflecting surface at a finite depth, the BRDF is defined in terms of the irradiance reflectance of the bottom. For infinitely deep water, the inherent optical properties of the water body below the region of interest are given, from which **HYDROLIGHT** computes the needed (non-Lambertian) BRDF describing the infinitely deep layer of water below the greatest depth of interest.

The absorption and scattering properties of the water body can be provided to **HYDROLIGHT** in various ways. For example, if actual measurements of the total absorption and scattering are available at selected depths and wavelengths, then these values can be read from files provided at run time. Interpolation is used to define values for those depths and wavelengths not contained in the data set. In the absence of actual measurements, the IOPs of the water body can be modeled in terms of contributions by any number of components. Thus the total absorption can be built up as the absorption by water itself, plus the absorption by chlorophyll-bearing microbial particles, plus that by CDOM, by detritus, by mineral particles, and so on. In order to specify the absorption by chlorophyll-bearing particles, for example, the user can specify the chlorophyll profile of the water column and then use a bio-optical model to convert the chlorophyll concentration to the needed absorption coefficient. The chlorophyll profile also provides information needed for the computation of chlorophyll fluorescence effects. Each such absorption component has its own depth and wavelength dependence. Similar modeling can be used for scattering.

Phase function information can be provided by selecting (from a built-in library) a phase function for each IOP component, e.g., using a Rayleigh-like phase function for scattering by the water itself, by using a Petzold type phase function for scattering by particles, and by assuming that dissolved substances like CDOM do not scatter. **HYDROLIGHT** can also generate phase functions that have a specified backscatter fraction. For example, if the user has both measured scattering coefficients $b(z,\lambda)$ (e.g., from a WETLabs ac-9 instrument) and measured backscatter coefficients $b_b(z,\lambda)$ (e.g., from a HOBILabs HydroScat-6 instrument), then **HYDROLIGHT** can use the ratio $b_b(z,\lambda)/b(z,\lambda)$ to generate a phase function that has the same backscatter fraction at each depth and wavelength. The individual-component phase functions are weighted by the respective scattering coefficients and summed in order to obtain the total phase function.

HYDROLIGHT does not carry out radiative transfer calculations for the atmosphere *per se*. The sky radiance for either cloud-free or overcast skies can be obtained from simple analytical models or from a combination of semi-empirical models. Such models are included in the **HYDROLIGHT** code. Alternatively, if the sky radiance is measured, that data can be used as input to **HYDROLIGHT** via a user-written subroutine. It is also possible to run an independent atmospheric radiative transfer model (such as MODTRAN) in order to generate the sky radiance coming from each part of the sky hemisphere, and then give the model-generated values to **HYDROLIGHT** as input.

The bottom boundary condition is applied at the deepest depth *of interest* in the simulation at hand. For a remote sensing simulation concerned only with the water-leaving radiance, it is usually sufficient to solve the radiative transfer equation only for the upper two optical depths, because almost all light leaving the water surface comes from this near-surface region. In this case, the bottom boundary condition can be taken to describe an optically infinitely deep layer of water below two optical depths. In a biological study of primary productivity, it might be necessary to solve for the radiance down to five (or more) optical depths, in which case the bottom boundary condition would be applied at that depth. In such cases, **HYDROLIGHT** computes the needed bottom boundary BRDF from the inherent optical properties at the deepest depth of interest. The bottom boundary condition also can describe a physical bottom at a given geometric depth. In that case, irradiance reflectance of the bottom must be specified (for a Lambertian bottom). In general, this reflectance is a function of wavelength and depends on the type of bottom—mud, sand, seagrass, etc. The user can also supply a subroutine to define a non-Lambertian BRDF.

Output from **HYDROLIGHT**

HYDROLIGHT generates files of "printout," which are convenient for a quick examination of the results, and larger files of digital data. The digital files are designed for spreadsheet analysis of selected results and for graphical or numerical analysis of all output, including the full radiance distribution. The default printout gives a moderate amount of information to document the input to the run and to show selected results of interest to most oceanographers (such as various irradiances, reflectances, mean cosines, *K*-functions, and zenith and nadir radiances). This output is easily tailored to the user's requirements. If desired, the printout can even give the full radiance distribution (separated into direct and diffuse components), radiance *K*-functions, path functions, and the like. A file of digital data contains the complete output from the run, including the full radiance distribution. This file is generally used as input to plotting routines that give graphical output of various quantities as functions of depth, direction, or wavelength. Macros are provided to convert selected digital output files into Excel® spreadsheets. All input and output files are in ASCII format to enable easy transfer between different computer systems.

An Example HYDROLIGHT Simulation

The following pages briefly describe a **HYDROLIGHT** simulation. This example is intended only to illustrate some of the capabilities of **HYDROLIGHT** version 4.2 for a hypothetical water body defined as follows:

Water IOPs: The water is Case 2 water containing chlorophyll-bearing phytoplankton, CDOM, and mineral particles. The CDOM and minerals do not covary with the chlorophyll concentration. The water is 8 m deep.

The chlorophyll concentration was taken to be $Chl = 0.5$ mg m^{-3} at all depths. Simple bio-optical models were used to convert *Chl* to absorption and scattering coefficients, and the phytoplankton were assumed to have a scattering phase function with a backscatter fraction of 0.005.

The CDOM was given an absorption profile that decreases exponentially with depth, to simulate CDOM in near-surface waters as might be due to river inflow. An exponential function of wavelength was used to obtain the CDOM absorption at all wavelengths. The CDOM was assumed to be non-scattering.

The mineral particles were given a concentration profile that varied from 0.2 g m^{-3} at the surface to 1.0 g m^{-3} at the bottom, to simulate resuspended bottom sediments. The mineral concentration was converted to absorption and scattering coefficients using measured mass-specific absorption and scattering coefficients for a brown clay. The mineral phase function was assumed to have a backscatter fraction of 0.025.

This information was entered into **HYDROLIGHT** via a generic four-component (water, phytoplankton, CDOM, and minerals) model for Case 2 water, which is built into **HYDROLIGHT 4.2**.

Depending on the depth and wavelength, one component or another dominates the absorption and scattering properties of the water. Figure 1 shows the component and total absorption coefficients as a function of depth for a wavelength of 445 nm. Figure 2 shows the total absorption coefficient as a function of depth for wavelengths from 350 to 700 nm. The total absorption is high near the surface at blue wavelengths because of the CDOM. It is high near the bottom because of the mineral particles, and it is high at red wavelengths because of the water itself. (All figures seen below were generated by IDL® routines that read a **HYDROLIGHT** digital output file formatted for input into IDL. Examples of such IDL routines are provided with **HYDROLIGHT**.)

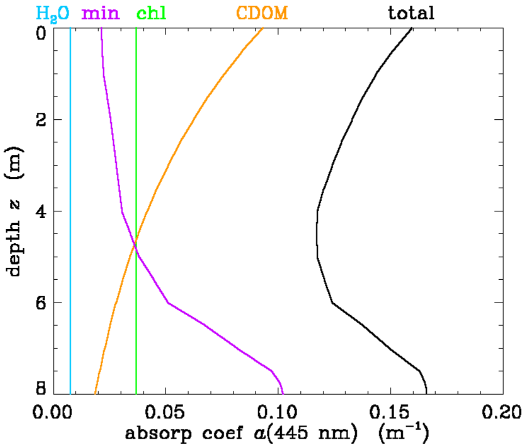

Fig. 1. Component and total absorption coefficients at 445 nm, for the hypothetical water body.

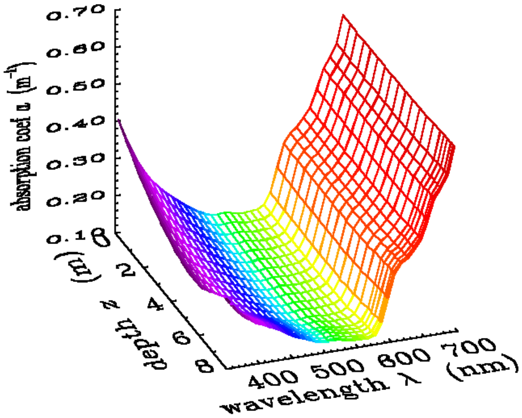

Fig. 2. Total absorption coefficient as a function of depth and wavelength.

Sky conditions: Using a default atmospheric model built into **HYDROLIGHT 4.2**, the sky was modeled using a clear-sky irradiance modified by a 30% cloud cover. The solar zenith angle was 30° and atmospheric conditions (aerosol type, humidity, ozone concentration, etc.) were given typical values. The atmospheric model computed the direct and diffuse irradiances at the sea surface with 1 nm resolution, which **HYDROLIGHT** then averaged over 10 nm wavelength bands. The directional distribution of the sky radiance was modeled using semi-empirical formulas built into **HYDROLIGHT**. The sea surface was covered by capillary waves corresponding to a 5 m s^{-1} wind speed. Figure 3 shows the total (direct sun plus background sky) downwelling plane irradiance at the sea surface.

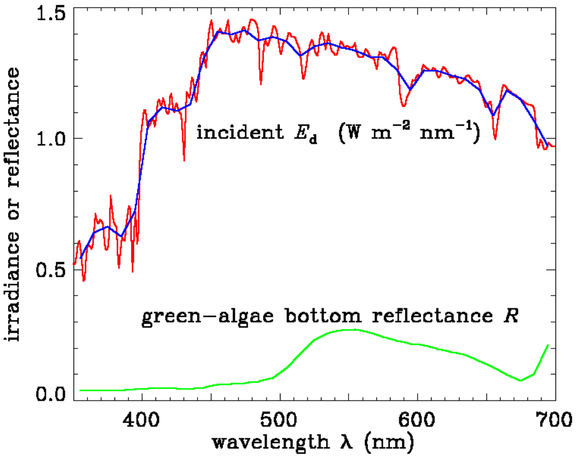

Fig. 3. Total irradiance incident onto the sea surface (red line: 1 nm resolution; blue line: 10 nm average) and bottom reflectance.

Bottom boundary: The bottom boundary at 8 m depth was given a Lambertian BRDF with an irradiance reflectance as measured for green algae. This reflectance is shown in Fig. 3.

Resolution of output: **HYDROLIGHT** was run from 350 to 700 nm with 10 nm band resolution. The run included fluorescence by chlorophyll and CDOM, and Raman scatter by the water. Output was saved every 0.5 m in depth between the surface and 6 m, and with increasing resolution near the bottom. The angular resolution of the computed radiance was 10° in the polar angle and 15° in the azimuthal angle.

This input completely specifies the radiative transfer problem to be solved by **HYDROLIGHT**. The run took 441 s on a 600 MHZ Pentium III PC. This corresponds to about 2 s per optical depth per wavelength.

Figure 4 shows a "slice" of the computed radiance distribution in the azimuthal plane of the sun, at a depth of 5 m, as a function of the polar angle and wavelength; note that the radiance scale is logarithmic. In the figure, a polar angle viewing direction of $\theta_v = 0$ corresponds to looking straight down, i.e., measuring the upwelling radiance. The peak near $\theta_v = 160$ is looking upward into the sun's refracted beam. The maximum radiance is at green wavelengths, as would be expected from the wavelength dependence of the absorption coefficient seen in Fig. 2; in other words, this is "green" water.

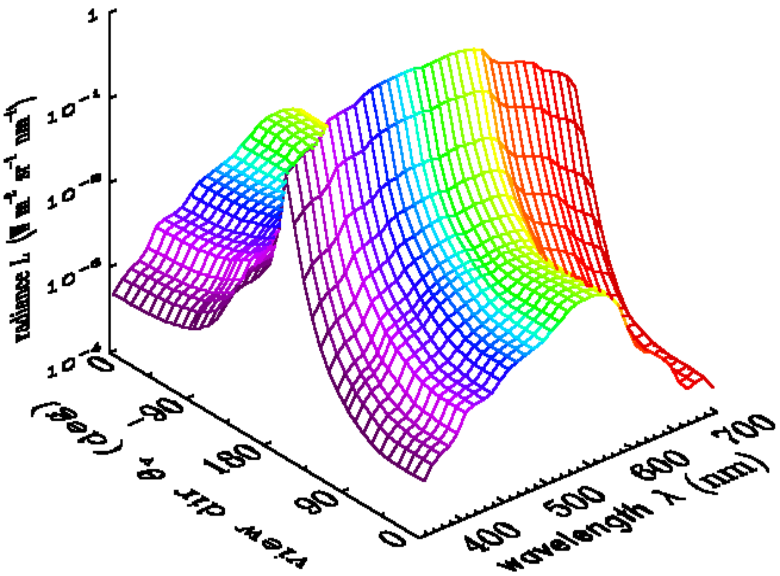

Fig. 4. Radiance distribution in the plane of the sun, at a depth of 5 m.

The full radiance distribution provides more information that is required for most purposes. The quantity relevant to phytoplankton growth or heating of the water is the scalar irradiance, which is computed by integrating the radiance over all directions. Figure 5 shows the scalar irradiance at three depths for the present simulation.

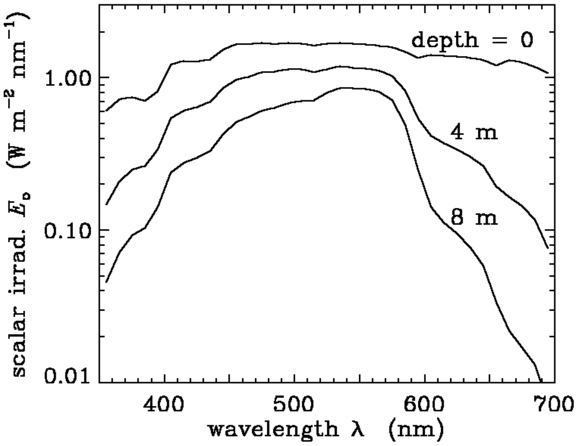

Fig. 5. Scalar irradiance as a function of wavelength for depths of 0 (just below the sea surface), 4 m, and 8 m (at the bottom of the water column).

Diffuse attenuation coefficients (K functions) are sometimes used to characterize a water body or sensor performance. Figure 6 shows the K functions for downwelling plane irradiance (K_d) and for upwelling radiance (K_{Lu}), for wavelengths of 445 and 545 nm. Note that K_{Lu} is negative at all depths at 545 nm, which means that the upwelling radiance is increasing with depth. This is a consequence of the large bottom reflectance and the relative clarity of the water at that wavelength.

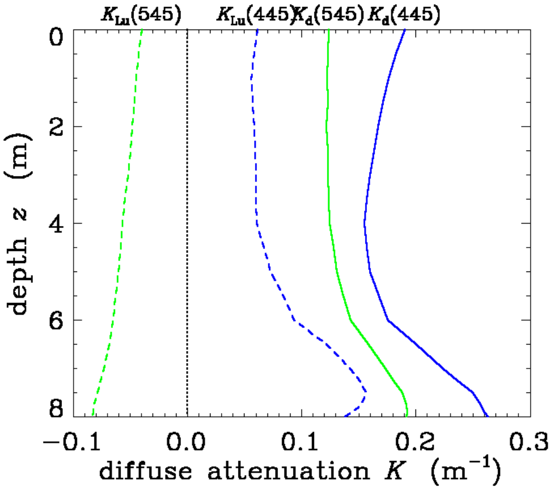

Fig. 6. Selected diffuse attenuation functions.

The remote-sensing reflectance is of course the quantity of interest in ocean color remote sensing. Because **HYDROLIGHT** computes the water-leaving radiance and the surface-reflected sky radiance separately, the exact remote-sensing reflectance is easily computed. Figure 7 shows the remote-sensing reflectance for this simulation.

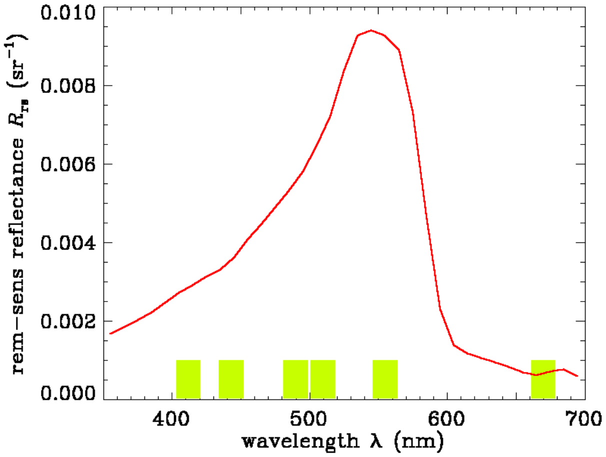

Fig. 7. Remote-sensing reflectance. The green bars at the bottom of the figure show the nominal SeaWiFS bands.

References

Mobley, C. D., 1994. *Light and Water: Radiative Transfer in Natural Waters*, Academic Press, San Diego, 592 pp.

Mobley, C. D., B. Gentili, H. R. Gordon, Z. Jin, G. W. Kattawar, A. Morel, P. Reinersman, K. Stamnes, and R. H. Stavn, 1993. Comparison of numerical models for computing underwater light fields, *Appl. Opt.*, 32, 7484-7504.

Availability of HYDROLIGHT

All versions of **HYDROLIGHT** are copyrighted code and are not in the public domain. Version 4 is available as a commercial product of Sequoia Scientific, Inc. For further information about the technical specifications and pricing of **HYDROLIGHT**, please contact Curtis Mobley at

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