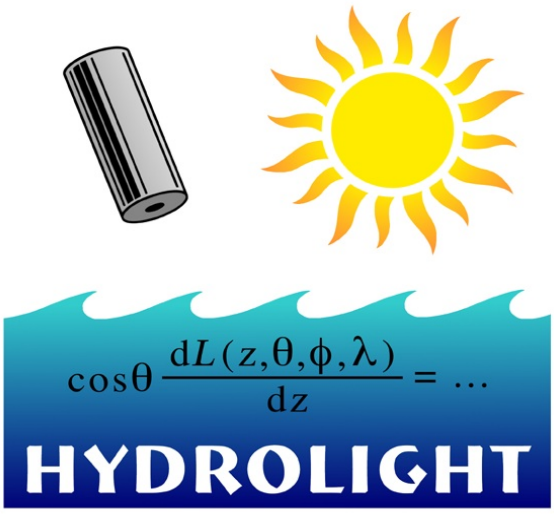

HYDROLIGHT 5
ECOLIGHT 5
USERS' GUIDE

Curtis D. Mobley
Lydia K. Sundman
Sequoia Scientific, Inc.

SEQUOIA

DRAFT VERSION

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DRAFT VERSION

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Technical Support

Technical support for HYDROLIGHT can be obtained in accordance with the user's license agreement from

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Lydia K. Sundman
lsundman@sequoiasci.com

If you encounter a problem during a HYDROLIGHT or ECOLIGHT run, please e-mail us the input file (`Iroot.txt`), and the printout file (`Proot.txt`) along with a description of the problem. If your run included a user-defined IOP model or function, or if you included bioluminescence, please also send us `root.for` file from the code\batch directory and any user-defined subroutines we would need to make the run. This will greatly increase the speed at which we can help troubleshoot any problem.

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1. INTRODUCTION

General knowledge of the radiance distribution within and leaving a water body is a prerequisite for the solution of many problems in underwater visibility, "ocean color" remote sensing, biological primary productivity, and mixed-layer thermodynamics. Moreover, because radiance is the fundamental radiometric quantity, all other quantities of interest to optical oceanographers—various irradiances, diffuse attenuation functions, reflectances and the like—can be computed from their definitions 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, this model solves the time-independent radiative transfer equation to obtain the radiance distribution within and leaving any plane-parallel water body. 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 of archival printout and of files of digital data, from which numerical, graphical or spreadsheet analyses can be performed.

The model 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. Analytical models of the IOPs can build up the total IOPs from contributions by any number of individual components. The input sky radiance distribution can be completely arbitrary in the directional and wavelength distribution of the direct 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.

This Users' Guide for Version 5 of the HYDROLIGHT model assumes that the reader is familiar with the basic terminology and notation of optical oceanography. If this is not the case, then the reader should first consult the review paper by Mobley (1995) or one of the books by Kirk (1994); Spinrad, Carder, and Perry (1994); or Mobley (1994). The Users' Guide gives a general overview of the capabilities of HYDROLIGHT, describes in detail how to run the model, and shows example output. The Users' Guide is independent of any other publication and should be adequate for users who wish to run HYDROLIGHT as a "black box" model or with minor modifications, such as adding routines to read in the user's data on a special format or adding additional output of interest to the user.

The separate Technical Documentation volume provides additional information and references for the IOP models, sky models, default data sets, etc. used in HYDROLIGHT. The formats for input and output data files are also given there. The text *Light and Water: Radiative Transfer in Natural Waters* (Mobley, 1994) describes in considerable detail the mathematical methods employed in HYDROLIGHT. That book is the primary technical documentation for the HYDROLIGHT model. The source code itself is documented by references to the equations of *Light and Water*.

The HYDROLIGHT source code is written entirely in FORTRAN, in order to make it easily portable to almost any computer with a FORTRAN 90 compiler[1]. All input and output files are written as ASCII files, to assure easy transfer of files between computers with different operating systems. In order to simplify running HYDROLIGHT, a "front-end" program is provided for running HYDROLIGHT in its standard mode (the usual way of running HYDROLIGHT, which will account for the vast majority of runs made by most users). The front end is a graphical User Interface (UI) that runs *only* on computers running the Microsoft® Windows® 95, 98 or Windows NT® operating systems.

Due to the increased number of user options for specifying the water body of interest, a text-based "question-and-answer" front-end program (as was provided with versions 4.0 and 4.1) is NOT currently provided for HYDROLIGHT 5. The UI front end program is provided only to make HYDROLIGHT more user friendly; it is not actually necessary to run either front-end program in order to run HYDROLIGHT itself. As with previous versions, users can create or modify the needed input files with a text editor and then submit HYDROLIGHT runs from a DOS command window. This procedure can be used to run HYDROLIGHT 5 on UNIX systems. However users are cautioned that manual modification of the input files is tricky due to the increased size and complexity of the input file, and is thus not recommended. This independence of HYDROLIGHT from the front-end program makes it possible to couple HYDROLIGHT with other models, as for example in coupled biological-optical-physical ecosystem models.

Throughout this report, the names of mathematical variables are written in italics, e.g., *U*, *z*, or *zeta*. The names of computer programs, directories, and files are written in a sans serif

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1. Although it is popular to deride FORTRAN as an ancient language no longer spoken in computer science departments, the fact remains that FORTRAN is, and likely will remain, the best language for doing numerical computations such as solving differential equations—which is what HYDROLIGHT does for 90% of its run time. We make no apology for keeping HYDROLIGHT in FORTRAN.

font, e.g., abcase1.f or Pupcast2.txt. Path names are written using the DOS format with a backstroke, e.g., ..\data\phasefun\avgpart.dpf. User input to and output from programs is show in `Courier`. Options on Graphical User Interfaces are shown in SMALL CAPS.

Some of the figures in this Users' Guide were generated in color but printed in black and white. The color figures can be seen on the pdf version of the Users' Guide, which is found in the documents directory on the CD.

1.1 Philosophical Comments, Warnings, and Excuses

It is important to understand that the HYDROLIGHT model per se is a radiative transfer model, not a model of oceanic optical properties. You, the user, must supply the inherent optical properties and boundary conditions to the HYDROLIGHT core code. (Indeed, the HYDROLIGHT model is not even restricted to the oceanic setting, although that is our interest here. If you supply HYDROLIGHT with the optical properties of orange paint, for example, HYDROLIGHT will happily solve for the radiance distribution within and leaving the paint.) This requirement for user input gives HYDROLIGHT great power—it can simulate any water body and each user can run the model for exactly the conditions of interest—but also requires considerable forethought and effort on the user's part, in order to specify IOPs and boundary conditions that correctly describe the water body of interest. Some users of previous versions have not understood their role in providing input to HYDROLIGHT, so let us say the following for emphasis:

> HYDROLIGHT does not know the inherent optical properties, or the chlorophyll profile, or the depth, or anything else about the water body *you* are interested in. *You* must provide this information to HYDROLIGHT. The various IOP models, phase functions, chlorophyll data sets, ac-9 data sets, etc. that come with HYDROLIGHT are *examples* of how to provide IOP and other information to HYDROLIGHT. *You* will need to replace these example routines and data sets with your own, in order to simulate the water body of interest to you.

HYDROLIGHT computes the radiance and other output (for a given set of input) more accurately than can be measured with standard instrumentation. However, as with any model, HYDROLIGHT's output is only as good as the input provided by the user. If you are using a simple "case 1" water model for the absorption and scattering coefficients, guessing the phase function, and using the mid-ocean atmospheric parameters in the sky radiance model,

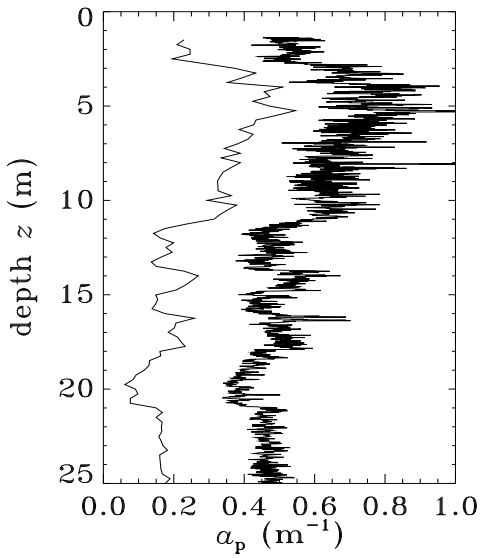


Figure 1. Smoothed and unsmoothed data. The right curve is 2,056 values of particulate absorption a_p obtained from an ac-9; this curve is too noisy to be used as input to HYDROLIGHT. The left curve (offset to the left by 0.3 for clarity) is the same data binned into 25 cm depth bins to give 95 a_p values; this curve is suitable for input to HYDROLIGHT and still contains adequate depth resolution of the absorption fine structure.

you should not be surprised (and are not allowed to complain) if the HYDROLIGHT-predicted water-leaving radiances differ significantly from what you measured in your experiment in case 2 coastal waters. Likewise, if you give HYDROLIGHT a file with thousands of ac-9 data points generated by sampling at 6 Hz during a depth profile, HYDROLIGHT will do its best to solve the radiative transfer equation with *exactly* the absorption and scattering profile you have given it. The result may be numerically disastrous if the ac-9 profile looks like random instrumental noise superimposed on a smoother signal, as illustrated in Fig. 1.

It is your job to clean up noisy data, smoothing and massaging as much as your conscience and scientific expertise allow, before using it as input to HYDROLIGHT. HYDROLIGHT is reasonably robust in checking for bad input, but there is still great opportunity for entering unphysical input and getting unphysical output.

HYDROLIGHT has been a work in progress since Curtis Mobley first started working out the numerical algorithms as a postdoc in 1979, and it will continue to be so. The invariant imbedding algorithms at the core of HYDROLIGHT are mature and well debugged after many years of use. However, some features of the graphical User Interface (UI) and IOP model options are new with version 5 and may evolve quickly as feedback is received from the users of version 5.

Version 4 was created in response to users' requests for a more user-friendly code, built with more powerful user options, and for a code that would run on inexpensive personal computers (as opposed to mainframes or UNIX workstations). Rather than just develop a PC

version of HYDROLIGHT version 3, major modifications were made to the code to develop a greatly improved version of HYDROLIGHT. Similarly, version 4.1 represented significant improvement in the package as a whole compared to version 4.0. Version 4.2 contained a few more improvements over 4.1 including an option to output the radiance into a separate file, specify non-Lambertian bottom reflectances, as well as a few cosmetic changes. Version 4.3 had additional improvements, including a more efficient scattering phase function selection when the backscatter fraction varies with depth.

Version 5 of HYDROLIGHT represents a substantial improvement over HYDROLIGHT 4. Most notably, version 5 includes ECOLIGHT , a ultra-fast version of HYDROLIGHT that solves the azimuthally-averaged problem. It is very useful when all the user wants to know is the remote-sensed reflectance, irradiances, or upwelling zenith radiance. Because of the inclusion of ECOLIGHT, the directory structure of HYDROLIGHT 5 is significantly different that in versions 4.x. HYDROLIGHT 5 also supports runs into the IR and UV (250nm to 1000nm) with extended IOP data files. Users will also notice that in most cases, the code will not require recompiling between runs. The code will only recompile when it is required to, for example, if a user-defined IOP model or concentration function, or bioluminescenc is included in the run.

To avoid the considerable expense required in supporting various compilers, Sequoia Scientific, Inc. had a licensing agreement with Lahey Computer Systems, Inc. that allowed a subset of the Lahey FORTRAN 90 version 4.5 compiler to be bundled with version 4.0 of HYDROLIGHT. Those Lahey files did not contain all of the features of the complete Lahey FORTRAN 90 software system. Beginning with HYDROLIGHT version 4.1, Lahey's Fortran 95 Express compiler (LF95 Express) is provided (on request) as a complete, stand-alone software package. LF95 Express is a fully optimizing Fortran 77/90/95 compiler. HYDROLIGHT is designed to be run with LF95 Express (although the core code remains Fortran 77), which improves HYDROLIGHT run times by as much as 30 percent in some situations (compared to LF90 v. 4.5). Note also that licenced users of HYDROLIGHT are now eligible for compiler support directly from Lahey for the LF95 Express product.

2. OVERVIEW OF HYDROLIGHT

This section gives brief descriptions of how HYDROLIGHT can be used, of what assumptions are build into the code, of what input is required, and of what output can be obtained from a HYDROLIGHT run.

2.1 Ways in Which HYDROLIGHT Can Be Used

Previous versions of HYDROLIGHT have 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 dynamics. Such information is fundamental to the coupling of physical, biological, and optical feedback models.

- HYDROLIGHT can be run with the IOPs 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 (such as substance concentrations or external environmental conditions). 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.

Such information 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 applications.

2.2 The Physical Model

Many problems of interest in optical oceanography and remote sensing can be solved using time-independent radiative transfer theory applied to plane-parallel geometries. The consideration of time-independent, plane-parallel problems is not as restrictive as it might seem on first glance. For example, although the oceans are horizontally inhomogeneous, the horizontal scales of significant optical variability (typically tens of meters to kilometers) are usually much greater than the vertical scales (centimeters to tens of meters). In this case we can think of the ocean as consisting of optically independent "patches" of water, for which each patch can be well modeled as a horizontally homogeneous water body whose optical

properties vary only with depth. (This is a one-dimensional geometry, with the one dimension being depth). We can then independently apply a one-dimensional radiative transfer model at the center of each patch in order to simulate the entire, horizontally inhomogeneous water body. In the analysis of imaging spectrometer data, one might even apply such a model to the water patch associated with each pixel in the image.

Such a piecewise simulation is justified so long as the horizontal size of each water patch is at least several photon mean free paths. This is usually the case. In the open ocean, photon mean free paths (the inverse of the beam attenuation coefficient) are never more than 50 m (at blue wavelengths, and much less at other wavelengths) in even the clearest waters; horizontal variability in such waters is often on scales of kilometers. In coastal waters subject to river runoff, sediment resuspension, and variable shallow bottom topography, optical properties and boundary conditions can change horizontally on scales of meters to tens of meters. However, such waters tend to be rather turbid and have photon mean free paths of tens of centimeters to a few meters. In either case, the use of a one-dimensional radiative transfer model is justified. The use of time-independent radiative transfer is valid whenever the time scales for changes in environmental conditions (typically seconds to seasons) are much greater than the time required for the light field to assume a steady state within the water body after a change in the optical properties or boundary conditions (milliseconds). Solving a sequence of time-independent, one-dimension radiative transfer problems in order to simulate a changing (in both time and space) water body is computationally much faster than solving one large time-dependent, three-dimensional problem.

Other physical considerations also dictate the generality required in an oceanic radiative transfer model. High absorption by water itself means that little light penetrates the ocean outside of the near-ultraviolet to near-infrared region from 350 to 800 nm. For the purpose of computing energy transfer through the air-water surface, it is often sufficient to account for capillary waves on the sea surface while neglecting the larger gravity waves. Multiple scattering is almost always important, but polarization may be neglected for many applications. Inelastic scattering processes such as Raman scatter by the water itself and fluorescence by chlorophyll and CDOM can in some circumstances make significant contributions to the light field.

The HYDROLIGHT physical model, which addresses the above considerations, can be summarized as follows:

- time-independent
- horizontally homogeneous IOPs and boundary conditions
- arbitrary depth dependence of IOPs
- wavelengths between 350 and 800 nm
- capillary-wave air-water surface
- finite or infinitely deep (non-Lambertian) bottom
- includes all orders of multiple scattering
- includes Raman scatter by water
- includes fluorescence by chlorophyll and CDOM
- includes internal sources such as bioluminescence
- does not include polarization
- does not include gravity waves or whitecaps

2.3 The Mathematical Model

The fundamental quantity that describes the time-independent, one-dimensional light field in the ocean is the spectral radiance $L(z,\theta,\phi,\lambda)$, with units of W m^{-2} sr^{-1} nm^{-1}. The spectral radiance completely determines the depth (z), directional (θ,ϕ), and wavelength (λ) behavior of the light field. Therefore, all other quantities of interest, such as various irradiances, diffuse attenuation functions (K-functions), and reflectances, can be computed from their definitions once the spectral radiance is known. In order to predict the spectral radiance, HYDROLIGHT solves the integro-differential radiative transfer equation (RTE) along with its boundary conditions. Because of their mathematical complexity, these equations must be solved numerically for any realistic situation (see, for example, Chapter 8 of *Light and Water*).

Any radiance sensor actually measures an average of $L(z,\theta,\phi,\lambda)$ taken over some finite solid angle $\Delta\Omega$, which is determined by the field of view of the instrument, and over some finite bandwidth $\Delta\lambda$, which is determined by the wavelength response of the instrument. Likewise, in order to solve the RTE numerically, we discretize it by averaging over direction and wavelength. In the HYDROLIGHT model, this directional averaging is performed by first partitioning the set of all directions (θ,ϕ), $0 \le \theta \le 180°$, $0 \le \phi < 360°$, into regions bounded by lines of constant θ and constant ϕ, plus two polar caps. These quadrilateral regions and polar caps are collectively called "quads." The individual quads Q_{uv} are labeled by discrete indices $u = 1, 2, ..., M$ and $v = 1, 2, ..., N$ to show their θ and ϕ positions, respectively. The standard (default) quad layout is shown in Figure 2. In this layout, which has $M = 20$ and $N = 24$, the polar caps have a 5°half angle and the θ boundaries lie at 5, 15, 25, ...,75, 85, 90, 95,

105, ..., 175 degrees. For mathematical reasons there is no quad centered on the "equator" at $\theta = 90°$. However, the radiances computed for the 85°-90° and 90°-95° quads can be averaged to give the "horizontal" radiance at a nominal angle of $\theta = 90°$. Thus the standard quad layout essentially gives 10° resolution in θ and 15° in ϕ.

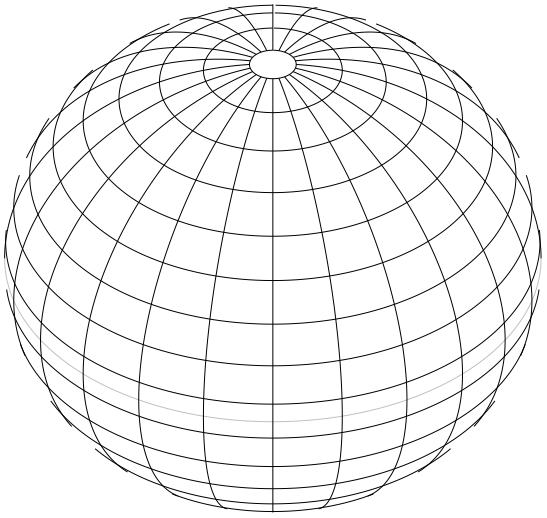


Figure 2. The HYDROLIGHT standard quad layout, which has a nominal angular resolution of $\Delta\theta = 10°$ and $\Delta\phi = 15°$.

Similarly, the wavelength region of interest is partitioned into a number of contiguous wavelength bands of width $\Delta\lambda_j$, $j = 1, 2, ..., J$. The $\Delta\lambda_j$ need not be the same size for different j values.

The fundamental quantities computed by the HYDROLIGHT model are then the quad- and band-averaged radiances at any selected set of depths z_k, $k = 1, 2, ..., K$:

$$L(k,u,v,j) \equiv \frac{1}{\Delta\Omega_{uv}\ \Delta\lambda_j} \int_{\Omega_{uv}} \int_{\Delta\lambda_j} L(z_k,\theta,\phi,\lambda) \sin\theta\, d\theta\, d\phi\, d\lambda\ .$$

In addition to the radiances within the water, HYDROLIGHT computes the upwelling radiance in all directions (all quads) just *above* the sea surface. This upwelling radiance 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 many remote sensing applications. The development of the quad- and band-averaged versions of the RTE and of the associated boundary conditions is given in full in *Light and Water*.

It must be noted that the quads "homogenize" the radiance within each quad, much like a frosted-glass window does. Thus, in the quad layout of Fig. 2, it is not possible to resolve the difference in the radiance for polar angles $\theta = 26°$ and $\theta = 34°$, because they both lie in the same quad extending from $\theta = 25°$ and $\theta = 35°$. However, there is a difference in $\theta = 34°$ and $\theta = 36°$, because those angles lie in different quads and thus are represented by different quad-averaged radiances. If it is necessary to have greater angular resolution in the radiance distribution, a different quad layout can be created by the user as described in the Technical Documentation. Note, however, that the computer storage and run time are proportional to the square of the number of quads, so increasing the angular resolution comes with a considerable computational cost.

2.4 The Coordinate System

HYDROLIGHT uses an x-y-z cartesian coordinate system with +x in the downwind direction and +z downward. Directions are specified via the polar angle θ and azimuthal angle ϕ, with $\theta = 0$ being straight down and $\phi = 0$ being downwind. In radiative transfer theory, direction (θ,ϕ) always refers to the direction the photons are traveling; the corresponding radiance is $L(\theta,\phi)$. Experimentalists, however, like to use (θ,ϕ) to denote the direction they are pointing their radiometer. The radiance measured by a radiometer pointing in direction (θ,ϕ) is $L(180-\theta, 180+\phi)$. Depending on which convention we choose for HYDROLIGHT output, either the theoreticians or the experimentalists will be unhappy.

In the HYDROLIGHT printout, we adopt the following convention, which is illustrated in Fig. 3. Direction (θ,ϕ) refers to the direction an instrument is pointing. However, θ is measured either from the nadir direction (the +z direction) or from the zenith direction (the -z direction), for instruments pointing downward or upward, respectively. When the instrument is pointing downward, we add a subscript "u" for "upward" to the radiance to remind us that we are referring to the upwelling radiance, i.e., to photons traveling upward. When the instrument is pointing upward, we add a subscript "d" to the radiance to remind us that we are referring to downwelling radiance, i.e., to photons traveling downward. Thus the theoreticians' radiance $L(\theta,\phi)$ is denoted $L_d(\theta,\phi)$ in the printout, and the theoreticians' radiance $L(180-\theta,180+\phi)$ is denoted $L_u(\theta,\phi)$. This u,d subscript convention is commonly used in optical oceanography. For example, E_d denotes the downwelling plane irradiance, which is measured by a cosine collector pointing upward. Likewise, in the printout, the horizontal radiance of photons traveling in the $(\theta=90,\phi=180)$ direction is denoted by $L_h(\phi=0)$.

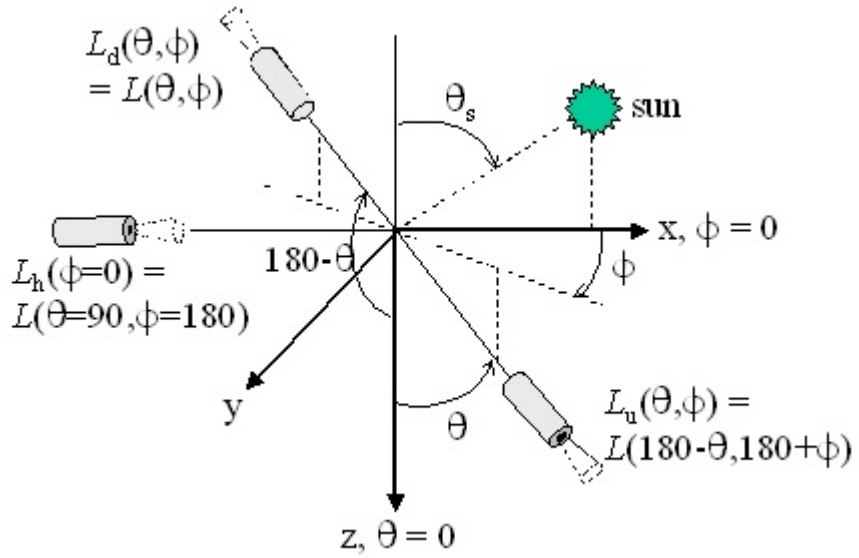


Fig 3. Coordinate system and notation conventions for radiance as used in HYDROLIGHT printout.

In the printout, a depth of z = 0 denotes a position within the water, just beneath the mean sea surface. A depth of z = *a* or "in air" denotes a position in the air, just above the mean sea surface. Thus the radiance $L_u(z=0,\theta,\phi)$ denotes the upwelling radiance just beneath the sea surface, and $L_u(z=a,\theta,\phi)$ denotes the *total* upwelling radiance in the air. The total upwelling radiance in the air is the sum of the water-leaving radiance, $L_w(\theta,\phi)$, plus the downwelling sky and sun radiance that is reflected upward by the sea surface itself (the sun glint), $L_{refl}(\theta,\phi)$. The sky radiance seen when looking in the (θ,ϕ) direction is $L_{sky}(\theta,\phi)$. These quantities are illustrated in Fig. 4.

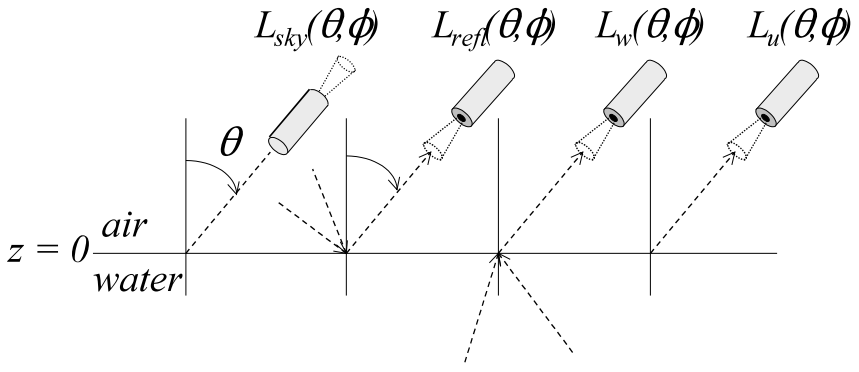


Fig. 4. Illustration of the various radiances just above the sea surface.

The standard version of HYDROLIGHT uses azimuthally averaged sea-surface wave slope statistics, in which case the azimuthal angle of the sun relative to the downwind direction, ϕ_s, is irrelevant, and ϕ_s is set to 0, as shown in Fig. 2. The sun's polar angle θ_s is always measured from the zenith, as is customary. Thus the sun's radiance would be $L_d(z=a,\theta_s,\phi=0) = L_{sky}(\theta_s,\phi=0)$.

It should be kept in mind that any radiance labeled for convenience by exact depth, direction, and wavelength values (z,θ,ϕ,λ) represents the radiance at the exact depth z (not a value averaged over a finite depth interval), but which is directionally averaged over the quad containing direction (θ,ϕ) and which is wavelength averaged over the wavelength band containing the nominal wavelength λ. (Radiances computed when selecting the "single wavelength" option can be thought of as being band averaged over a 1 nm wide band.) Radiances are thus quad- and band-averaged spectral radiances with units of W m^{-2} sr^{-1} nm^{-1}, not band integrated values. Likewise, irradiances are spectral values with units of W m^{-2} nm^{-1}.

Finally, radiative transfer theory is formulated in terms of energy units, not quanta. In the HYDROLIGHT output, the spectral scalar irradiance $E_o(z,\lambda)$ with units of W m^{-2} nm^{-1} is also converted to quanta units of mol photons m^{-2} at the very end of the calculations for the convenience of photobiologists, and the corresponding PAR profile is computed.

2.5 Input

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 direct input or via user-written subroutines or user-supplied data files):

- **The inherent optical properties of the water body**. These optical properties are the absorption and scattering coefficients and the scattering phase function (which are equivalent to the volume scattering function, the beam attenuation coefficient, and the albedo of single scattering). These properties must be specified as functions of depth and wavelength.

- **The state of the wind-blown sea surface**. Version 4.0 and later of 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 described in terms of a bi-directional reflectance distribution function (BRDF). For finite-depth bottoms, the BRDF is computed from the given irradiance reflectance of the bottom, if the bottom is a Lambertian surface, or from a user-supplied BRDF, which can be non-Lambertian. For infinitely deep water, the inherent optical properties of the water body below the region of interest are used to compute the needed (non-Lambertian) BRDF that describes the reflectance properties of the water below the region of interest.

The absorption and scattering properties of the water body can be provided to the HYDROLIGHT model in various ways. For example, if actual measurements of total absorption are available at selected depths z and wavelengths λ, then these values can be read from a file provided at run time. An interpolation scheme can be used to define absorption values for those z and λ values not contained in the data set. In the absence of actual measurements, the total absorption 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, you 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 individual absorption component has its own depth and wavelength dependence. Similar modeling can be used for scattering.

Phase function information is often provided by using a Rayleigh-like phase function for scattering by the water itself, by using either a Petzold-like phase function or a phase function selected to have a given backscattering ratio for scattering by particles, and by assuming that dissolved substances like CDOM do not scatter. The individual-component phase functions are weighted by the respective scattering coefficients and summed in order to obtain the total phase function.

HYDROLIGHT also requires the downwelling radiance incident onto the sea surface as input. The HYDROLIGHT model does not carry out any radiative transfer calculations for the

atmosphere *per se*. However, the sky radiance for either cloud-free or overcast skies can be estimated from simple analytical models or from semi-empirical models; such models are provided as a part of the HYDROLIGHT code. Alternatively, if the sky radiance is actually 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 (Acharya, *et al.*, 1998) in order to generate the sky radiance coming from each quad of the sky hemisphere, and then give the MODTRAN-generated values to HYDROLIGHT as input.

For finite-depth water columns, the bottom boundary BRDF is usually computed from the specified irradiance reflectance of the bottom and the assumption that the bottom is a Lambertian reflector. In general, the bottom reflectance is a function of wavelength and depends on the type of bottom—gray mud, ooid sand, seagrass, etc. For infinitely deep water columns, the (non-Lambertian) BRDF is computed using the IOPs at the deepest depth *where output is requested* 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 "diffuse attenuation depths" [a depth of $2/K_d(\lambda)$], 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 the depth corresponding to two diffuse attenuation 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 information from the inherent optical properties at the deepest depth of interest.

2.6 Output

Output from HYDROLIGHT consists of both "printout" (an ASCII file formatted for viewing with a text editor or for hardcopy printing) and files of digital data. The default printout gives a moderate amount of information to document the input to the run and to show the quantities of interest to most oceanographers (such as various irradiances, reflectances, mean cosines, irradiance *K*-functions, and zenith and nadir radiances). The printout is useful for taking a quick look at the results of a run, or for cutting and pasting a particular part of the output into another document or spreadsheet. Optionally, the printout can give the full radiance distribution (separated into direct and diffuse components), radiance *K*-functions, elastic-scatter path functions, and the like. The printout is easily tailored to the user's requirements. Section 7.1 describes the printout in more detail.

A file of digital data contains the complete output from the run, including the full radiance distribution as a function of depth, direction, and wavelength. This file is generally used as input to plotting routines to obtain graphical output of various quantities as functions of depth, direction, or wavelength. Routines for graphical output are not a part of the HYDROLIGHT code because of the wide variety of graphics packages in use and because different users generally want different kinds of plots. However, a few plotting routines written in the IDL language are included with HYDROLIGHT as a convenience for users who have that popular software package. The digital output file is formatted to facilitate the opening of the file by IDL (which stores arrays by rows, rather than by columns as in FORTRAN). Section 7.3 comments further on the use of IDL in plotting HYDROLIGHT output.

Two other files of digital output are formatted for use within Microsoft EXCEL® spreadsheets. One file is formatted to facilitate the analysis of data one wavelength at a time. For example, you might want to plot various irradiances as a function of depth at one wavelength. The other file is formatted to facilitate the analysis of one variable at a time, as a function of depth and wavelength. For example, you might want to plot the absorption coefficient as a function of depth and wavelength. EXCEL macros are provided to open these files within EXCEL and automatically generate spreadsheets containing the quantities of interest to most oceanographers. Section 7.2 describes how to convert the HYDROLIGHT output files into EXCEL spreadsheets.

3. INSTALLING HYDROLIGHT

This Chapter gives the details of how to install the HYDROLIGHT code on your Windows-based computer.

3.1 Computer Requirements

The HYDROLIGHT source code is written entirely in standard FORTRAN in order to make the code as portable as possible. Previous versions of HYDROLIGHT have been run on a variety of computers including CDC and Cray mainframes; Sun, Silicon Graphics, and DEC UNIX workstations; IBM and IBM-clone Personal Computers (PCs) with 486 and Pentium processors running Microsoft Windows 3.1 95, 98, and NT, and Apple Power Macintoshes.

Although the core code of HYDROLIGHT can run on a wide range of computers, *Version 5 is currently supported only on PCs running the Microsoft Windows 95, 98, or NT* operating system due to the complexity of the new input and subsequent dependence on the UI to set up runs (which only runs on Windows 95/98/NT). A PC/Windows platform for HYDROLIGHT is also strongly recommended for several reasons:

- The HYDROLIGHT software system (optionally) includes a FULL version of the Lahey FORTRAN 95 Express compiler, which is designed for Pentium (or compatible) processors and Microsoft Windows operating systems.

- EXCEL spreadsheets software is usually found on PCs with Windows 95/98/NT.

- Related software, such as the IDL graphics package, is much less expensive for PCs than for mainframes or UNIX workstations.

The HYDROLIGHT package of source code and data files requires about 50 Mbytes of hard-drive storage as distributed. The Lahey compiler, as optionally distributed with HYDROLIGHT, requires additional memory. After compilation on the user's computer, the executable file for the main code is approximately one Mbyte. The minimum required amount of random access memory (RAM) is not large. However, compilation (and perhaps also run) times can be very slow if insufficient RAM forces extensive swapping. Experience shows that 30 Mbytes of RAM is normally more than enough for satisfactory compilation and running of HYDROLIGHT.

The digital output files can be 10 Mbytes or larger for runs requesting output at many depths and wavelengths. Thus, disk storage can be consumed quickly in a series of simulations requesting extensive output (e.g. for high-resolution graphics). Moreover, some of the internal scratch files used during the solution of the radiative transfer equation can be many tens of Mbytes if many depths and wavelengths are included in the run. Thus at least 100 Mbytes of free hard-drive space and 32MB of RAM is recommended for running HYDROLIGHT.

The UI is designed for optimum use on monitors with 1024 x 768 pixels. Lower-resolution monitors cause some of the UI forms to display as larger than the monitor screen. Higher-resolution monitors make the UI forms appear smaller than intended, which makes the forms harder to read.

The UI front-end program issues commands to invoke the compiler and linker. It is generally necessary to recompile a few subroutines for each run. In previous versions of HYDROLIGHT, information such as which IOP and sky models are being used was imbedded for each run into at least ten core routines during compilation via "include files". In Version 4.1, the include statements in core routines were replaced with calls to generic subroutines and the include files (all except dimens.inc) have been replaced with a single FORTRAN source code file, iroot.for, which contains definitions for all those generic subroutines. In Version 5, the code was rewritten such that only runs that called user-defined subroutines would require the code to recompile. This includes runs that use a user-defined IOP model, specify component concentrations with function calls, or include bioluminescence. For these cases, the file iroot.for is written by the UI into the HE5\code\batch directory and is necessary to completely specify the run.

The commands necessary for invoking the compiler are different for different brands of compilers, and even for different versions of the same compiler. *Because the Lahey compiler is available (at the licensee's request) with HYDROLIGHT, no support is given for other FORTRAN compilers.*

3.2 Installation on Microsoft Windows Operating Systems

This section describes how to install HYDROLIGHT on a PC running the Microsoft Windows operating system. It is assumed that you will be running HYDROLIGHT with the Lahey LF95 Express compiler that comes with HYDROLIGHT.

The HYDROLIGHT software package is distributed as one (uncompressed) directory named HE5 (with subdirectories as seen in Fig. 3) on a CD. To install the code on your PC, do the following:

Step 1. Install Lahey's LF95 Express compiler in accordance with the installation instructions provided with that software. With version 4.1, the compiler is no longer provided as a subdirectory, but rather the full version of the LF95 Express compiler is provided (which includes Lahey's customer support of the LF95 Express product).

Step 2. Insert the HYDROLIGHT CD into its drive. The installation program should start automatically. If it does not, go to START ➜ RUN and run setup.exe from the CD (e.g., if the CD is in drive D you would type "`d:\setup.exe`" at the run prompt).

Step 3. You will be asked to select the folder (e.g., c:\ or c:\Program Files) into which HE5 will be installed. A new folder HE5 will be created and placed in the folder you selected UNLESS you select a folder named HE5 (in which case that HE5 folder will be overwritten). You will also be asked to read the license agreement. The installer provided will take care of all aspects of the installation including: copying the files, updating and registering any system files needed by HYDROLIGHT, removing the read-only flags from the HE5 files, and creating shortcuts for HE5 in both the START ➜ PROGRAMS window and on the desktop. If you have any trouble with the installation, please refer to the Technical Documentation FAQ section.

3.3 Uninstalling HYDROLIGHT

You may on occasion need to uninstall HYDROLIGHT, for example when moving the code from an old computer to a new one. Also, if you need to reinstall HYDROLIGHT for some reason, you should first uninstall the old version. Because the installation software updates the Windows registry files when HYDROLIGHT is installed, it is important to uninstall the code properly. This is done as follows:

go to MY COMPUTER ➜ CONTROL PANEL ➜ ADD/REMOVE PROGRAMS
select HYDROLIGHT and click on ADD/REMOVE
follow the directions to remove all (system) files associated with HYDROLIGHT

This operation will remove certain system files, the executable file for the UI (file HE5WinFE.exe), and update the registry, but it will leave the HYDROLIGHT icon on the desktop and, more importantly, the HE5 directory and all of its contents (including output from previous runs) will be left intact. You can remove the HE5 directory and all of its contents by opening WINDOWS EXPLORER, clicking in the HE5 directory, clicking on DELETE, and following

the instructions to delete everything. Be sure you have saved any needed output from previous HYDROLIGHT runs before deleting the HE5 directory! Finally, the HYDROLIGHT icon can be dragged from the desktop to the trash bin. Removal of the LF95 Express compiler must be performed as a separate software removal.

4. HYDROLIGHT ORGANIZATION

This section describes how the HYDROLIGHT code is organized. The different types of routines and data files are described, and the file-naming conventions and directory structure are established.

4.1 The HYDROLIGHT Software Package

The HYDROLIGHT package consists of many different main programs, subroutines, and data files. The different routines and files can be classified as follows:

- **Core FORTRAN main programs and subroutines.** Each of these routines is flagged in the source code by a statement of the form "Core routine on file filename.f" where "filename" is the name of the file containing the routine. These core routines include both HYDROLIGHT-specific routines and various public-domain subroutines taken from sources such as LAPACK (Linear Algebra PACKage) and BLAS (Basic Linear Algebra Subroutines; see Dongarra and Grosse, 1987). The public-code routines are used by the HYDROLIGHT-specific routines for mathematical tasks such as matrix inversion, eigenvector-eigenvalue analysis, and solving differential equations. Only the most sophisticated users would even contemplate tampering with any of these highly mathematical core routines.

- **Example user-supplied subroutines.** Each of these routines is flagged in the source code by a statement of the form "Example user-supplied ... routine on file filename.f" The ellipsis describes the type of routine, e.g. "sky radiance" or "absorption and scattering." The routines defining the abconst, abcase1, abcase2, etc. IOP models are all examples of a user-supplied absorption and scattering routine. These standardized subroutines are provided with the HYDROLIGHT code and can be used as is, or can be modified as desired to alter the input to HYDROLIGHT. These examples illustrate how the template routines can be expanded to provide routines for IOP input, sky input, etc.

- **Data files**. These files provide input such as chlorophyll- or mass-specific absorption and scattering spectra for use in IOP models, scattering phase functions, sea-surface reflectance and transmission properties for different wind speeds, bottom reflectances,

and atmospheric properties used by the default sky irradiance models. The distributed files will be sufficient for many users. However, users can add to this collection by putting their own data onto various "HYDROLIGHT standard formats" or by making "specialized" runs (for example, to add additional phase functions) as described in the Technical Documentation.

- **Templates for creating user-supplied subroutines and data files.** Each of these routines is flagged in the source code by a statement of the form "Template for user-supplied ... routines." The ellipsis describes the type of routine, e.g. "sky radiance" or "absorption and scattering." These templates show the required formats for various routines that provide the core program with information about the absorbing and scattering properties of the particular water body being simulated, about the sky radiance distribution, and the like. Some users want to write their own versions of such routines in order, for example, to read in their own measured absorption and scattering profiles or to insert their own analytical models of the inherent optical properties. This can be done by inserting the desired FORTRAN code into the corresponding template.

- **Example simulations.** The input, run script, and output files for a few typical HYDROLIGHT simulations are given for reference. Users should reproduce these simulations on their own computers after installation, in order to verify that HYDROLIGHT is running properly on their computer.

- **Plotting routines written in IDL** (Interactive Data Language; IDL® is a product of Research Systems, Inc.). These routines are, strictly speaking, not a part of the HYDROLIGHT code. A small collection of example IDL routines is included for the convenience of users who have the IDL software package. Users may wish to discard these routines and use other software for graphical analysis of the HYDROLIGHT digital output.

The FORTRAN routines of the HYDROLIGHT code are grouped into three parts found on directories maincode, surfcode, and discpf. These routines carry out both "standard" and "special" runs. In version 5 of HYDROLIGHT, each of these code groups also has an ECOLIGHT version included.

Standard runs are those that result in a solution of the radiative transfer equation. The routines for performing standard runs are found in the code directory. The code routines use the available collection of phase-function, sea-surface, and other data files along with the user

input provided at run time to solve the radiative transfer problem defined by the input. Standard runs are often made in a series, with only minor changes in the input for each run (e.g., a change in the solar zenith angle or in the chlorphyll profile, with all other input being held constant from one run to the next). Standard runs will constitute almost all of the HYDROLIGHT runs made by most users.

Special runs are those that are made for adding a new phase function or a new wind speed to the available collection of data files. Special runs are made only once for a given phase function or wind speed. The routines in directory discpf are used to prepare a scattering phase function for use by the HYDROLIGHT main code. (This preparation is called discretizing the phase function.) These calculations need to be done only once for a given phase function and quad partition. The use of the routines in discpf is described in the Technical Documentation.

The routines in directory surfcode perform the calculations associated with the air-water surface boundary. These surface calculations depend only on the wind speed and on the quad layout; they are independent of the sky radiance distribution and of the water inherent optical properties. Therefore, the surface calculations need to be performed only once for a given wind speed and quad layout. The results are saved (in directory data\surfaces as the files named surfwind.U, where U is the wind speed in m/s) for repeated use by the main code, which performs the remainder of the computations. Only users who need wind speeds geater than 15 m/s or who want to customize the quad layout will ever need to run the surface routines. The use of the routines in surfcode is described in the Technical Documentation.

Note that if you wish to change quad partitioning from the default shown in Figure 2, all phase functions and surface files must be recreated via special runs.

4.2 File Naming Conventions

Although it is claimed that Windows 98 and NT allow the use of long directory and file names, this is true only if you stay in the point-and-click world. Unfortunately, the command window of Windows 98/XP, for example, is still DOS 6.2. This means that names longer than 8 characters get truncated when you are working in a command window, which is where HYDROLIGHT compiles and runs. To allow users to include data files with long file names (up to 32 characters) a special subroutine (IOshorten.f90) was added to allow HYDROLIGHT to interface with Windows and look up the 8.3 format DOS filename. Thus if you tell the frontend program that your ac-9 data is on a file named mygreatac9data.txt, the file name is truncated to mygrea~1.txt by the operating system (where the number after the tilde is set by the system), yet HYDROLIGHT will still be able to find the right file.

Part of the input to a HYDROLIGHT run is a single-word "root" name that is used to construct the names of all input and output files associated with that run. Thus, after running the front-end program, the input to HYDROLIGHT will be found on a file named lroot.txt, where "root" has been replaced by the chosen identifying name, e.g. lupcast2.txt if root = upcast2. After the run finishes, the printout will be found on file Proot.txt (e.g., Pupcast2.txt), and so on. The following input file is created for every HYDROLIGHT run:

lroot.txt — the file containing the Input specifying the run (see the Technical Documentation for a detailed description of this input). Written by the UI to the run\batch directory.

This input file is the same for either a HYDROLIGHT or ECOLIGHT run! If the run calls a user-defined IOP model, includes bioluminescence, or calls a user-defined function to deinie any of the component concentrations, a run-specific version of the HYDROLIGHT code will automatically be compiled and the following additional input file will be generated:

Root.for — the file containing subroutines that call the appropriate IOP and sky models specified for this run, including the sky parameters. Written by the UI to the code\batch directory.

These two files contain all of the information specific to each run. In the run directory, there are two executables named run_HL.exe and run_EL.exe along with a list of runs to be made, named runlist.txt.

When you make a HYDROLIGHT run, you execute run_HL.exe (by choosing "`run HYDROLIGHT now`" from the UI, double clicking run_HL.exe, or by going to start->run->run_EL.exe) which reads the file runlist.txt containing a list of lroot.txt filenames that are part of the current "batch" (may only contain one). The runs listed in runlist.txt are submitted by run_HL.exe sequentially to HYDROLIGHT. Thus, you can always re-run a case made earlier and you can build up batches of previously defined runs by simply adding their lroot.txt filenames to the runlist.txt file in the run directory. The new executable run_XX.exe does the following:

1. takes care of submitting runs in a batch (even if the "batch" only has one run),
2. **only if necessary** copies the run-specific FORTRAN file from the code\batch directory into the code directory as incfiles_user.for, and compiles a new executable, mainHL_user.exe

3 sends the run names to spawnHL_X.bat (in the code directory) to be run, and

4. Waits for the run to finish before starting the process for the next run listed in runlist.txt and repeating steps 2-4 until all runs are completed.

Step 2 only occurs if a suer-defined subroutine needs to be compiled. For the vase majority of users, HYDROLIGHT will never need to recompile. For this reason, most runs are handled by the executable mainHL_stnd.exe and utility spawnHL_stnd.bat. If the code is recompiled, the run will create and use the executable mainHL_user.exe and utility spawnHL_user.bat. These issues are handled automatically by run_HL.exe.

When you make an ECOLIGHT run, you execute run_EL.exe (by choosing "`run ECOLIGHT now`" from the UI, double clicking run_EL.exe, or by going to start->run->run_EL.exe). It reads the same file as HYDROLIGHT but submits runs to and executables . In this way, once you have defined a run, you can choose to run it under HYDROLIGHT or ECOLIGHT at any time without re-running the UI or changing your input. If fact, from the final screen of the UI, you can submit the run to both HYDROLIGHT and ECOLIGHT for a side-to-side comparison.

After the run finishes, the printout for each run will be found on file Proot.txt (e.g., Pupcast2.txt), and so on. HYDROLIGHT output is written to the output\Hydrolight directory and ECOLIGHT output is written to the output\Ecolight directory. The following output files can be created for each run by checking the appropriate boxes on the OUTPUT OPTIONS form of the UI:

Droot.txt	the file containing the full Digital output from the run (usually used as input to a graphics package). Written to the digital directory.
Eroot.txt	the file containing the irradiance and PAR printout from the run. Written to the printout directory.
Lroot.txt	the file containing the full radiance printout from the run. Written to the printout directory.
Mroot.txt	the file containing the Multi-wavelength-format output for postprocessing with excel. Written to the excel directory.
Proot.txt	the file containing the Printout from the run (usually used for a "quick look" at the output). Written to the printout directory.

Sroot.txt — the file containing the Single-wavelength-format output for postprocessing with EXCEL. Written to the excel directory.

On the final form of the UI, users have the option of selecting how much output is generated for their run. For example, a user who does not process output in EXCEL may elect not to generate the Sroot.txt and Mroot.txt files.

4.3 Directory Structure

The HYDROLIGHT package is installed by default on the user's computer as a main directory named HE5. On a PC, this directory might have the full path name c:\HE5 or c:\Program Files\OceanOptics\HE5, depending on how the user likes to organize his or her computer system. You can, if desired, rename the main directory (for example, if you wish to have more than one copy of HYDROLIGHT installed for work on different projects, or if different users are working on the same computer and each has his or her own copy of HYDROLIGHT.) In any case, the HYDROLIGHT code uses path names relative to the main directory (which is referenced as ".." in either DOS, or the Windows operating systems), so that the actual name of the main directory does not matter. The main HE5 directory has a number of subdirectories *whose names must not be changed.* All of the computations within a HYDROLIGHT run are done within the subdirectories. Figures 5 (a) and (b) show the layout and names of the subdirectories. Figure 5(a) shows the directory used in a standard run while Figure 5(b) shows the complete structure of the HYDROLIGHT software package.

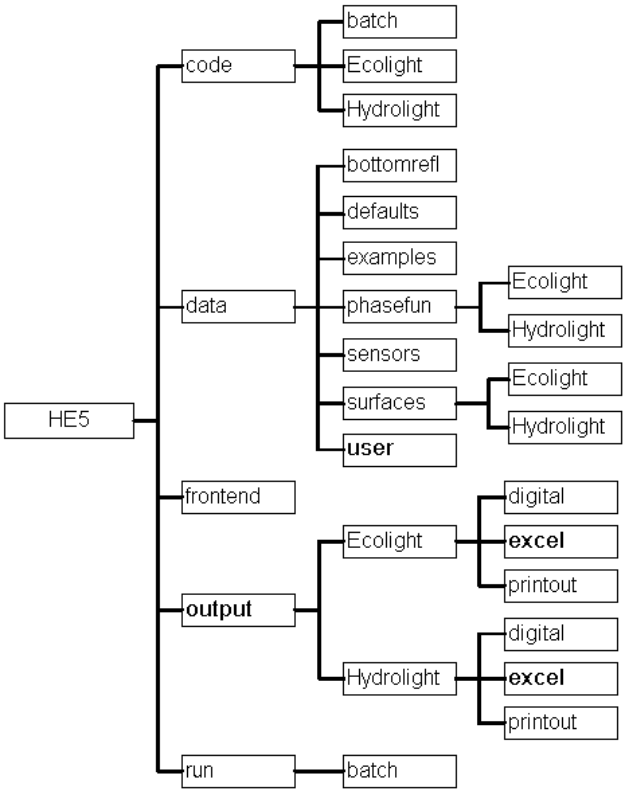


Figure 5(a). The HE5 directories used in standard runs.

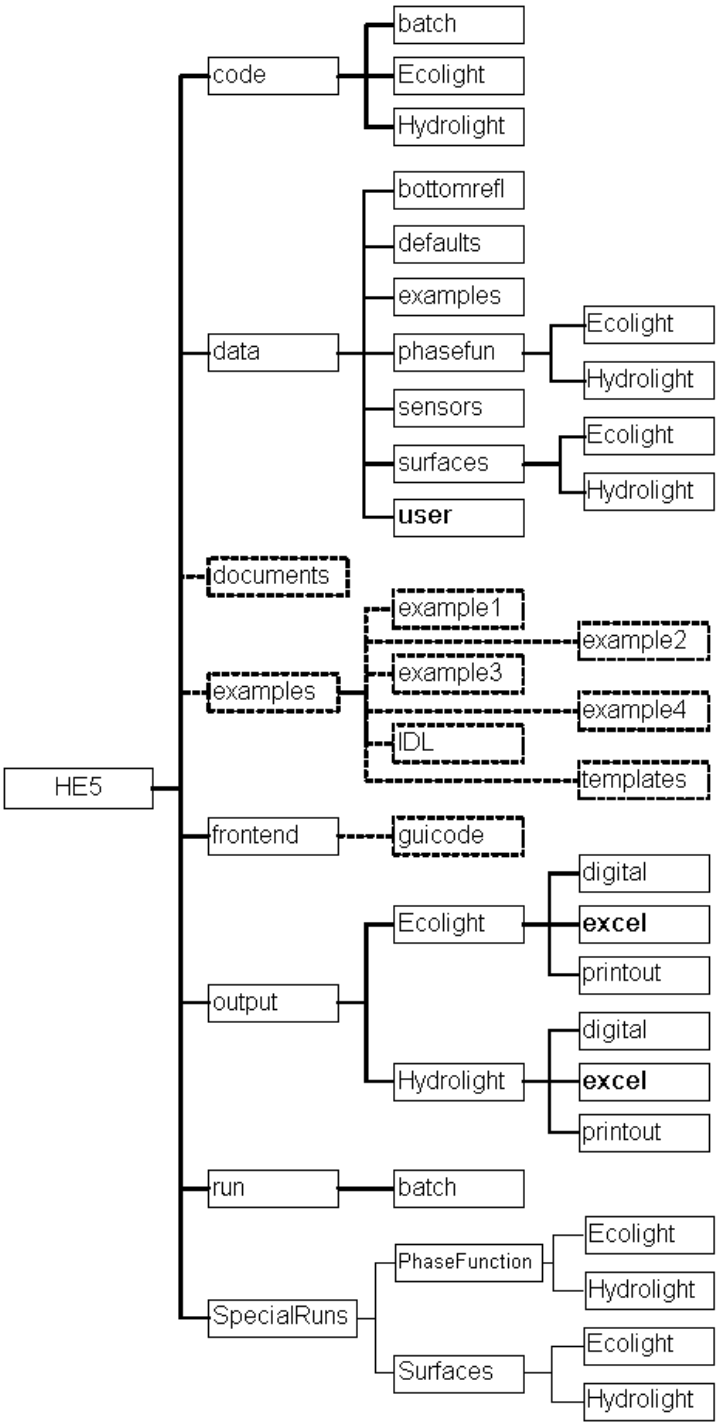


Figure 5(b). The complete HE5 directory structure. The heavy boxes show the directories involved in HYDROLIGHT standard runs. The light boxes show directories used in special runs. The dotted boxes show directories containing files that may be of interest to some users, but which are not required for HYDROLIGHT runs.

The contents of the various directories are as follows:

code contains the executables and FORTRAN source code for the HYDROLIGHT standard runs.

- batch is the directory where the UI writes the run-specific FORTRAN file (root.for) for runs when necessary.
- Ecolight is the directory containing the source code for ECOLIGHT.
- Hydrolight is the directory containing the source code for HYDROLIGHT.

data contains the input data files for a run. Initially, this directory contains files with the pure water absorption and scattering coefficients and a few example files of ac-9 and chlorophyll data. *Users can add their own data files to this directory, which is the default location where HYDROLIGHT looks for data files.* This directory also has five subdirectories for holding particular types of input:

- botmrefl contains files of bottom reflectances. Initially, this directory contains a few example files for different bottom types. Users can add their own files of measured bottom reflectances to this directory.
- defaults contains files of specific absorption and scattering coefficients, as taken from the literature. Users can add their own files of measured or modeled values to this directory.
- examples contains examples of the various data file formats expected by HYDROLIGHT for input. Some of these files are used in the example runs described in Section 6, but are not intended for general use.
- phasefun contains files of discretized phase functions created by the code in directory discpf. Initially, this directory contains files

(named *.dpf for discretized phase function) for various phase functions. Users can add their own files of discretized phase functions to this directory by making special runs.

sensors — contains files of sensor-specific wavebands. Users can add their own files of wavebands to this directory. The name of the "sensor" must be added to sensorlist.txt for the name to appear in the pull-down box of the UI. Note: the file corresponding to a given sensor must be the sensor's name with the txt extension added (e.g., the wavebands associated with SeaWiFS runs are stored in the SeaWiFS.txt file in this directory).

surfaces — contains files of sea-surface information for different wind speeds. These files were created by making special runs using the code in the surfcode directory.

user — Users can add their own data files to this directory.

documents — contains PDF versions of the Users' Guide, Technical Documentation volume, as well as various readme and release notes.

examples — contains templates for the user-supplied subroutines example IDL routines, and the input, run script, and output files for the three example simulations presented in Section 6.

example1 — contains the input, run script, and output files for the simple single-wavelength, radiative transfer simulation example.

example2 — contains the input, run script, and output files for the multi-wavelength, Classic Case 1 water simulation example.

example3 — contains the input, run script, and output files for the multi-wavelength, NEW Case 1 water simulation example.

example4 — contains the input, run script, and output files for the Case

2 water example run using SeaWiFS wavebands.

idl — contains the IDL routines used in producing this Users' Guide. These routines are designed to read the full-output digital data files.

template — contains templates for creating various user-defined subroutines (e.g., for IOP or sky models) and data files (e.g., for ac-9 or chlorophyll profiles).

frontend — contains the executable UI front-end program for Windows (file HE5WinFE.exe) as well as the default files for the UI.

guicode — contains the Visual Basic® 5.0 source code for the UI front end.

output — contains all of the output files written by HYDROLIGHT during runtime.

excel — contains files associated with EXCEL spreadsheets. This directory initially contains the two macros (files singlewl.xls and multiwl.xls) that open the corresponding HYDROLIGHT spreadsheet output files (files Sroot.txt and Mroot.txt, respectively) as EXCEL workbooks. HYDROLIGHT writes its spreadsheet output files to this directory.

digital — is the directory where HYDROLIGHT writes the full-output digital data file (the Droot.txt files) from each run.

printout — is the directory where HYDROLIGHT writes the printout (file Proot.txt) from each run.

run — contains the input files, and run list (runlist.txt), and run executable (run.exe) needed to run and compile the HYDROLIGHT main code. These files are written by the front-end program.

batch — is the directory where the UI writes the input files (Iroot.txt) for

each run.

SpecialRuns contains PDF versions of the Users' Guide, Technical Documentation volume, as well as various readme and release notes.

phaseFunction contains the code needed for discretizing a phase function and creating new *.dpf files. See the Technical Documentation for more information.

surface contains the source code needed to create surface data files (the files named ..\data\surfaces\surfwind.U, where U is the windspeed in m s^{-1}) for additional wind speeds or different quad layouts. Most users will never need this code. See the Technical Documentation for more information.

5. THE GRAPHICAL USER INTERFACE

Standard HYDROLIGHT runs are runs that solve the RTE for a given set of water IOPs and surface and bottom boundary conditions. Because this is the mode of running HYDROLIGHT that is employed most of the time (and all of the time by most users), it is described first. Most users will find the standard quad layout seen in Fig. 2, the available wind speeds (0 to 15 m s^{-1}), and the selection of phase functions to be adequate. If this is not the case, then special runs to define new quad layouts, wind speeds, or phase functions must be made before making the desired standard runs. These special runs are described in Section 4 of the Technical Documentation.

A standard run takes information about the inherent optical properties of the water body and adds information about the sea-surface, the incident sky radiance distribution, and the bottom boundary condition. This information together completely defines a physical situation for which the radiative transfer equation (RTE) has a unique solution. The HYDROLIGHT main code then solves the quad-averaged RTE and generates the final output of the HYDROLIGHT model. The standard computations are entirely deterministic; no Monte Carlo simulations are used to solve the RTE within the water body.

The primary way to initiate a HYDROLIGHT standard run is by running the UI front-end program (Windows 95/98/NT systems only). It is also possible to create the input file, run script, and included FORTRAN file (incfiles.for) with an ASCII text editor and then run

HYDROLIGHT from a command window. However, due to the many input options, this is a much more difficult endeavor than in previous versions and is therefore not recommended. The input format is described in detail in Appendix A of the Technical Documentation.

Standard runs are often made in a series in which only one input variable such as the solar zenith angle, water absorption coefficient, or bottom depth is changed between each run. Therefore, the front-end program has the option of saving the input values from the current run and using those values as the default values for the input to the next run. After making the first run of a series, the user then can quickly "click through" the UI windows, pausing only to change the one input value that is to be different in the next run. Similarly, a user who is familiar with the input format can quickly open the input file with a text editor, change a number, re-save the file, and submit the new run. However, it is critical that this only be attempted by people very familiar with how information is passed into HYDROLIGHT to prevent inconsistencies between what problem you are solving and what problem you *think* you are solving.

Regardless of how a run is initiated, the user must give HYDROLIGHT input that defines a unique radiative transfer problem for the environmental conditions of interest. When running the UI front end, these specifications are made by selecting allowed values for various parameters, by entering the names of files containing data such as chlorophyll profiles, or by entering a list of depths where the output is to be saved.

The purposes of the front-end program is to

- guide users through the specification of all of the input needed to define the radiative transfer problem
- use the users' responses to generate the various files needed to run HYDROLIGHT
- run HYDROLIGHT to solve the specified radiative transfer problem

The UI frontend program consists of a number of windows, each of which prompts the user for a particular type of information, e.g., what IOP model to use, what bottom boundary condition to use, or what depth resolution is desired in the output.

The frontend programs have the option of saving the input, so that the responses from one pass through the front end become the default responses for the next pass. This makes it possible to cycle through HYDROLIGHT runs in a nearly automated fashion in order to carry out a detailed study of how the marine light field depends on some quantity of interest, such at the

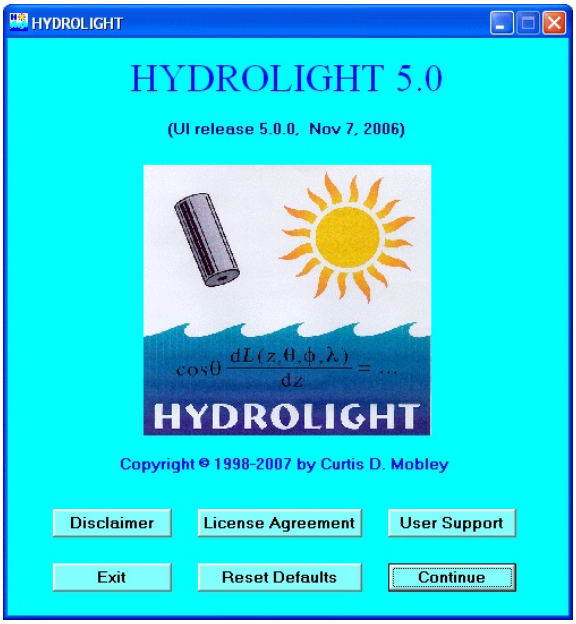
sun's location or the IOPs of the water body. After the first pass through the front end, only minimal input (such as changing the solar zenith angle or the depth of the bottom) is required on the subsequent passes.

The usual problem-solving sequence is to work through the UI windows, run the HYDROLIGHT code to solve the radiative transfer problem just defined, and then return to the start of the UI to specify the input for the next run. It is also possible to define a series of HYDROLIGHT runs from within the UI and then run the whole series afterwards. In this case, the various input files are accumulated and then run as one "batch" run consisting of many individual HYDROLIGHT runs.

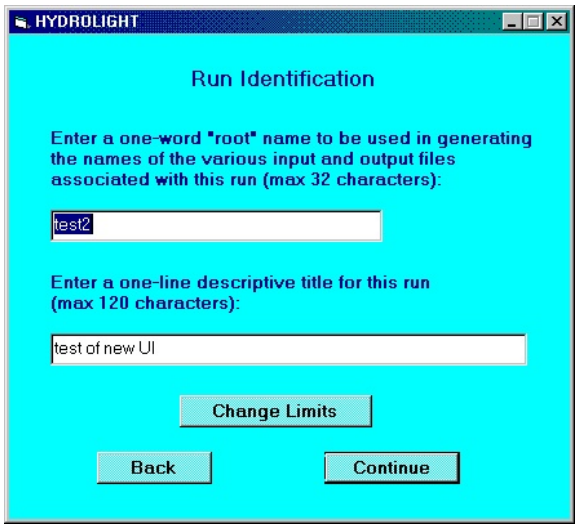
This following pages briefly describe the input requested in the various windows of the UI front end. Many of the UI options have "tool tips" to provide additional information. Full documentation of the available models and features is given in the Technical Documentation.

5.1. Run Identification

The Opening form. When running HYDROLIGHT for the first time, click the RESET DEFAULTS button. You will need to read the DISCLAIMER and the LICENSE AGREEMENT before continuing. On subsequent runs, you can proceed immediately by clicking CONTINUE. Any time you wish to return to the default values (as distributed with the code) for the various parameters, just click RESET DEFAULTS.



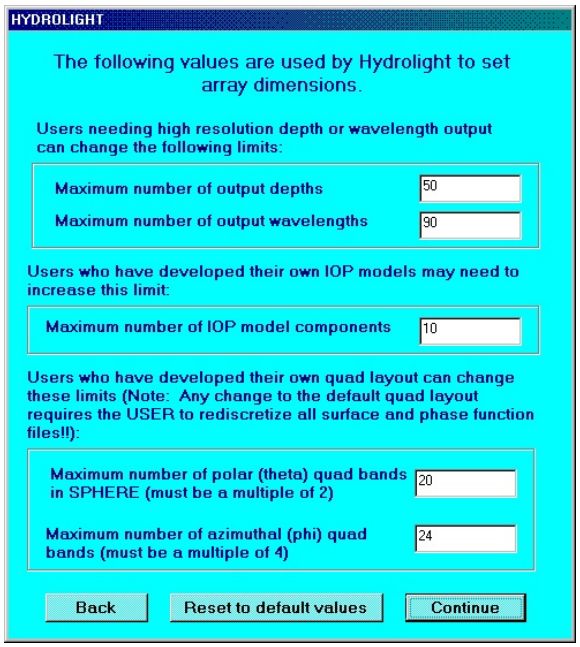
The RUN IDENTIFICATION form. This form first asks for the "root" name to be used in generating the file names for the run. For DOS-based machines (e.g., for Windows 95), keep this name to 7 or fewer letters to avoid potential problems with longer names being truncated. For Windows 98/NT, you can use longer names, but keep the root as one word (i.e., do not have any blanks in the name). Also enter a descriptive title for the run. This title will appear on the printout and other output files generated by the run.



HYDROLIGHT has the ability to accumulate a series of runs into a batch and then submit them all at once. HYDROLIGHT will take care of remembering what runs you want to make and which models to use for each. To do this, HYDROLIGHT stores the subroutine-based run specifications normally written to the file incfiles.for in the maincode directory in a special

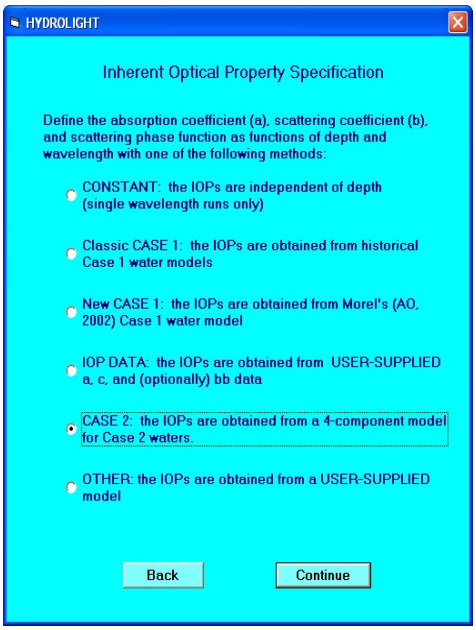
\batch folder within the maincode directory, and the input run files (iroot.txt) are written into a \batch subfolder in the run folder of HYDROLIGHT. The batch will not be submitted until either you select run batch script from the final form or you run the script Rbatch.bat from outside of the graphical frontend user interface.

The PARAMETER LIMIT form. If you double click CHANGE LIMITS on the RUN IDENTIFICATION form you will be taken to a special form to specify maximum values of several parameters. This is a form most users will never need to use. This form allows you to change the maximum number of output depths, number of IOP model components, etc. for your run. These values are used to dimension arrays within HYDROLIGHT. Note: these values do not need to EQUAL the values for your run — they simply have to be at least as big. If you change any of these values, the compiler will force all of the routines to recompile (as opposed to the single routine recompiled on a "normal" run).



When you click CONTINUE from the RUN IDENTIFICATION form, a pop-up box will show you the names of the files that will be generated.

5.2. IOP Specification



The IOP MODEL SPECIFICATION form. This form requires you to pick an IOP model, i.e., a model for the absorption and scattering coefficients and scattering phase functions that describe the water body. The input required by various IOP models differs; the needed information will be requested on the next form, depending on which option is selected on this form. Six options are available on this form:

❍ CONSTANT. This IOP model describes the water body by its total absorption and scattering coefficients and phase function; the water is taken to be homogeneous. This model is useful for idealized radiative transfer studies done at one wavelength.

❍ CLASSIC CASE 1. This IOP option selects a simple, frequently used ("Gordon-Morel") bio-optical model for Case 1water, which uses simple equations to obtain the absorption and scattering coefficients for chlorophyll particles and co-varying CDOM from a user-specified chlorophyll concentration. This model is for use only in Case 1 water and is only intended for comparative purposes. Users are encouraged to use ABCASE2 for both Case 1 and Case 2 water simulations since that model provides more options for describing the IOPs.

❍ NEW CASE 1. This IOP option selects the Morel (2002) Case 1 water model, obtains the absorption and scattering coefficients by dividing the chlorophyll into small and large chlorophyll-bearing particles with their own absorption and scattering models (the ratio of small to large particles is determined by the total chlorophyll concentrtation), and co-varying CDOM. This model is for use only in Case 1 water.

❍ IOP DATA. The IOPs are constructed as the sum of pure water values plus "everything else"—particles and dissolved substances—as measured by a WETLabs ac-9 instrument, (other data on the same formats, e.g. from a WETLabs HiSTAR, can be processed with this

model.) Optionally, backscatter data measured by a HOBILabs HydroScat-6 instrument can be used in conjunction with the ac-9 data to select phase functions with the measured backscatter fraction.

❍ CASE 2. This general Case 2 water model includes many options for specifying concentration profiles and IOP models for each of four components: water, chlorophyll-bearing particles, CDOM, and mineral particles. To make Case 1 runs using the Case 2 model, simply select the option to let CDOM "agree with the Case 1 model" and set the mineral concentration to zero.

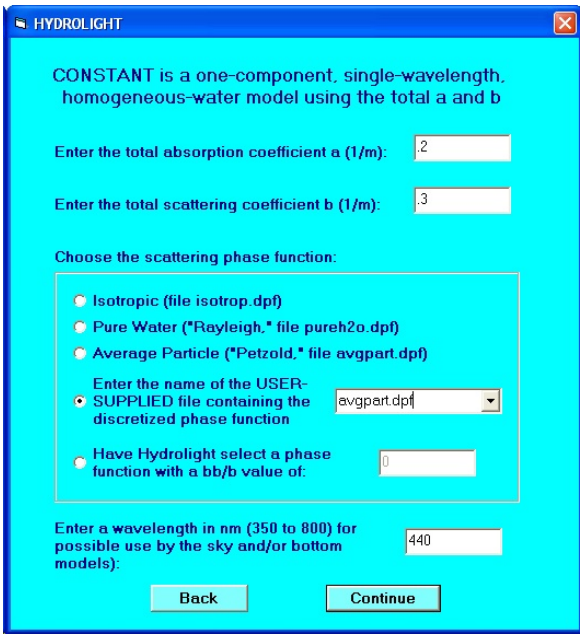
❍ OTHER. If you decide not to use any of the above provided IOP models, you can define your own IOP model. In this case, you may use the UI to specify your component IOPs by selecting the ABOTHER option, which will ask you to provide information for each component as well as the name of your "ab" routine. It is your responsibility to insure that your routine properly uses the input provided in the UI. Please see the Technical Documentation for more information about developing your own IOP model.

If you change the IOP model between saved runs you will likely get the following warning:

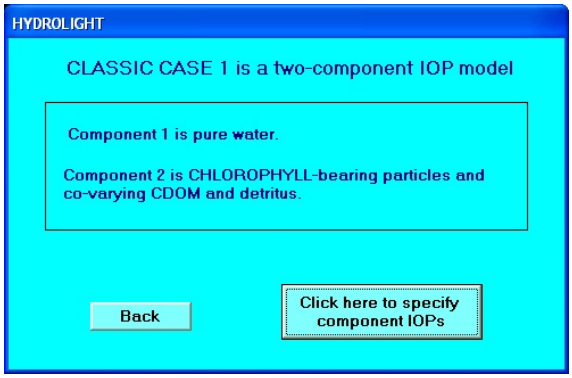
This is just to remind you that when you change your IOP model, you need to make sure that the IOPs specified are consistent with your new model. HYDROLIGHT will require you to view each of the IOP specification pages (including specific absorption/scattering) to make sure you are not accidentally using values from a previous run.

The next set of forms shows the input required by these different IOP models.

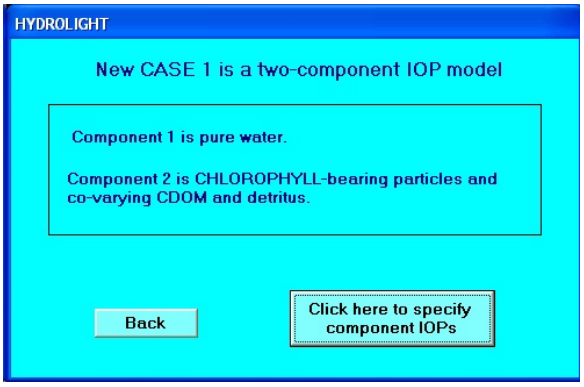
The CONSTANT form. This form requests the input needed by the CONSTANT IOP model. The water is modeled as a single component having the specified total absorption, total scattering, and phase function. Even though the water IOPs are specified once *a*, *b*, and the phase function have been selected, the form also requests a wavelength for the run; the wavelength may be needed by the sky and/or bottom models. Since the wavelength will be specified here, the wavelength specification form (described below) will not appear with the CONSTANT model. The code for the CONSTANT model is in file abconst.f.



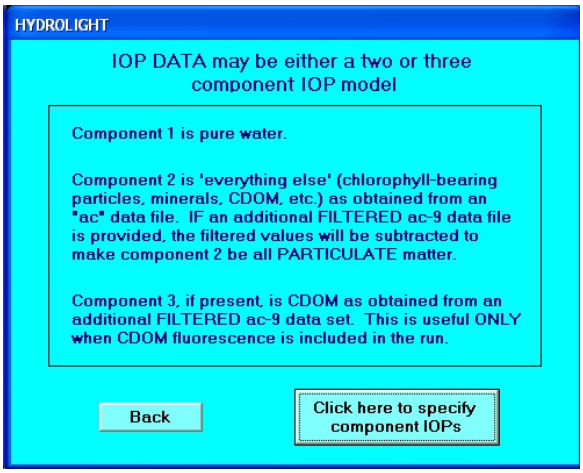
The CLASSIC CASE 1 form. This form requests the input needed by the bio-optical models used in the CLASSIC CASE1 IOP model. The water is modeled by three components: pure water, pigmented particles, and co-varying CDOM. The absorption and scattering properties of the particles and CDOM are parameterized by the chlorophyll concentration, which in general is a function of depth. The code for the CLASSIC CASE1 model is in file abcase1.f. Clicking on the "specify component IOPs" button will take the user to the IOP component specification form described below. Since the Gordon-Morel model includes models for the specific absorption and scattering of chlorophyll, they are not included on the component forms.



The NEW CASE 1 form. This is a recently proposed (Morel, 2002) alternate model for Case 1 water. This IOP model has four components: pure water, large particles, small particles, and CDOM, each of which covaries with the chlorophyll concentration. The chlorophyll concentration is the only input required by this model.

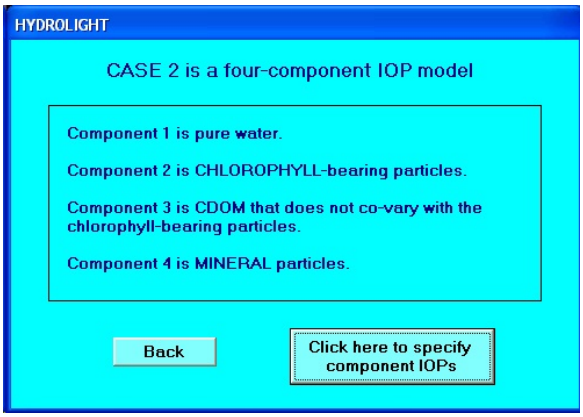


The IOP DATA form. In this IOP model, the water is modeled by two components: pure water and "everything else" (particles and CDOM). Measured absorption (a) and beam attenuation (c) data as obtained from a WETLabs ac-9 (or similar) instrument are used to determine the IOPs of the second component. An optional third component will be added if and only if CDOM fluorescence is included, in which case absorption due to CDOM will be specified after the inelastic scattering form, where the user will have the option of providing a filtered ac-9 file for that purpose.

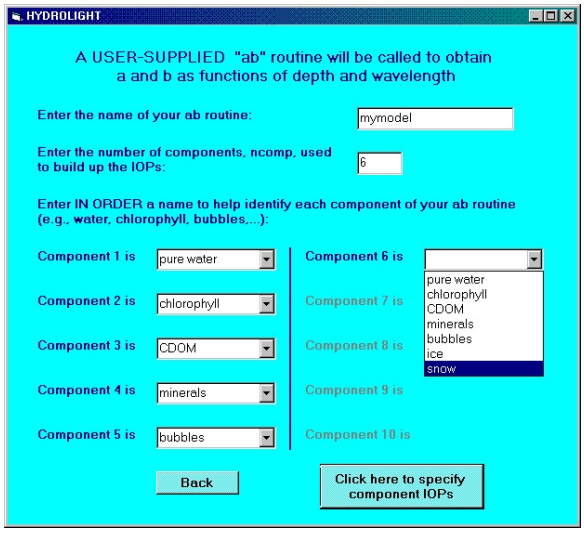


The component specification form for IOP DATA is slightly different than for the other components. The concentrations are given by the ac-9 data file and there is an added option of specifying the phase function by using a HydroScat-6 data file. If the HydroScat option is selected, the backscattering ratio will be calculated for each depth and a new phase function loaded whenever b_b/b changes by more than the tolerance set in the last box. Note that this tolerance can have a significant impact on the total run time if set very small since new data files must be read each time a change is needed. The smoothness of the b and b_b data can also greatly affect the run time when this model is used. The code for this model is in file abacbb.f.

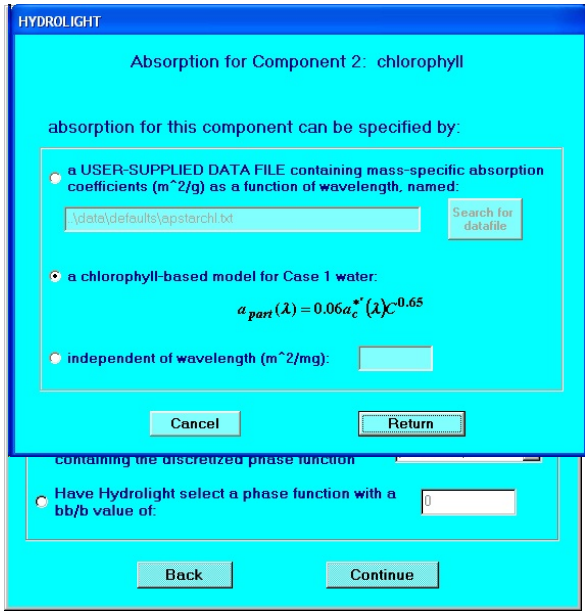
The CASE 2 form. A basic, flexible case 2 water model is provided. The model has four components: pure water, chlorophyll-bearing particles, CDOM, and mineral particles. There are many options for specifying the IOPs of each component.



The OTHER form. This form allows you to select a user-written IOP model with up to ten components. (The abcase2 subroutine on file maincode\abcase2.f is an example of such a model.) First, enter the name of the file containing the subroutine ("mymodel" in this example form), and the number of components used in the subroutine to build up the IOPs (6 in this example). Then select a descriptive name to be used for each component of your IOP model. After each component is named on this page, the user will be asked to specify the IOPs for each one (in order) via the IOP SPECIFICATION FORM. See the Technical Documentation volume for information about writing your own IOP subroutines.



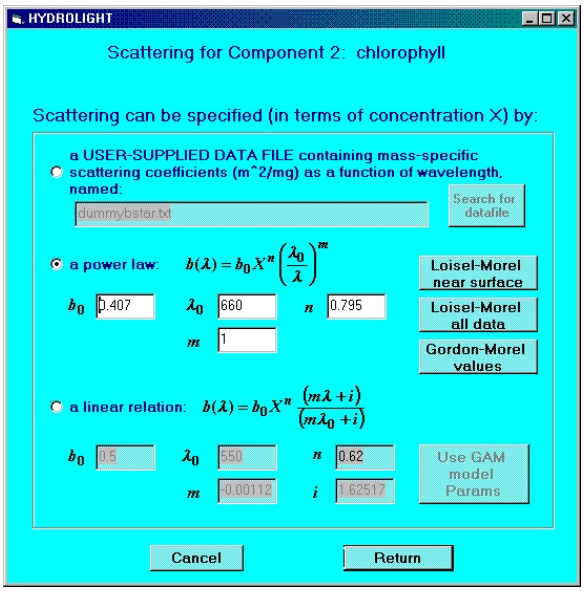
The IOP COMPONENT SPECIFICATION form. Once you have selected your model, you will be asked to provide information specifying the IOPs of each component one at a time. In general, this will consist of providing the component concentration, information regarding the specific absorption and scattering of the component, and selecting a phase function.



The needed concentration must be obtained either by assuming it is constant with depth, from a *user-supplied* subroutine or from a *user-supplied* file containing measured depth vs. concentration values. The chlzfunc.f file in the template directory contains the format required for concentration subroutines, and chlzdata.f shows the format for concentration data files. The SEARCH FOR DATA FILE button allows you to browse your computer for data files. The pull-down menu shows the available phase functions. In addition to the provided phase function files, Version 4.2 and later have the option to generate a phase function with any given backscattering fraction, b_b/b between 0.0001 and 0.40. For this option, HYDROLIGHT always uses a Fournier-Forand phase function (with the given b_b/b), as described in the Technical Documentation.

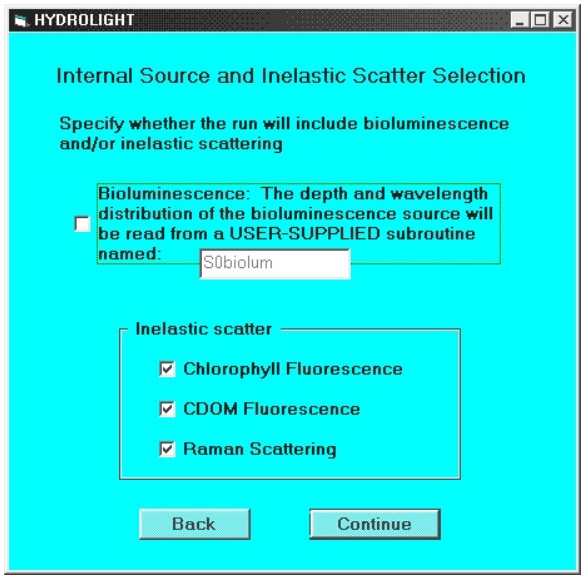
The ABSORPTION SPECIFICATION form. Clicking the button to specify the absorption properties of a component will lead the user to a new window with options that depend on what is known about the component. Depending on what the component is and what model is being used, some of the options may be greyed out (unavailable) or not visible. Also, since the Haltrin Case 1 model specifies both the specific absorption/scattering models and the phase functions, the user is not given the option of setting those values.

The SCATTERING SPECIFICATION form. Similarly, clicking the button to specify the scattering properties of a component will lead the user to a new window with options that depend on what is known about the component. An example is that no phase function or b* options will be given if the component is CDOM (which is nonscattering).



5.3 Inelastic Scattering and Bioluminescence

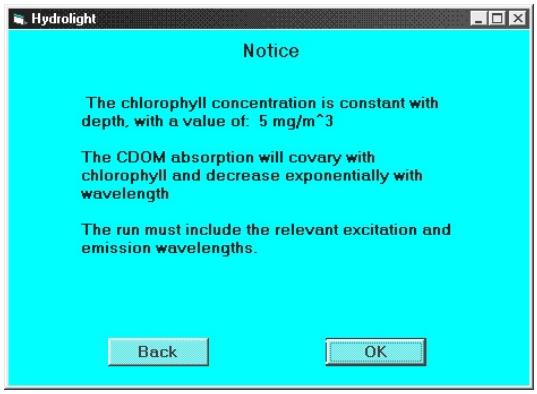
The INTERNAL SOURCE AND INELASTIC SCATTER form. This form allows you to specify whether the run will include internal sources (e.g., bioluminescence) or various kinds of inelastic scattering processes. Except for Raman scattering, which is determined by water alone, choosing one of these features will require you to specify additional information.



When fluorescence is included, the absorption values specified by the run will be used, along with the fluorescence efficiencies set in setdeflts.f and the wavelength redistribution functions built into wrfdisc.f. If, for example, CDOM is not a component of your model, checking the "CDOM fluorescence" box causes a special form to appear allowing you to specify CDOM absorption. This subroutine will be called to get the CDOM absorption as a function of depth and wavelength, which must

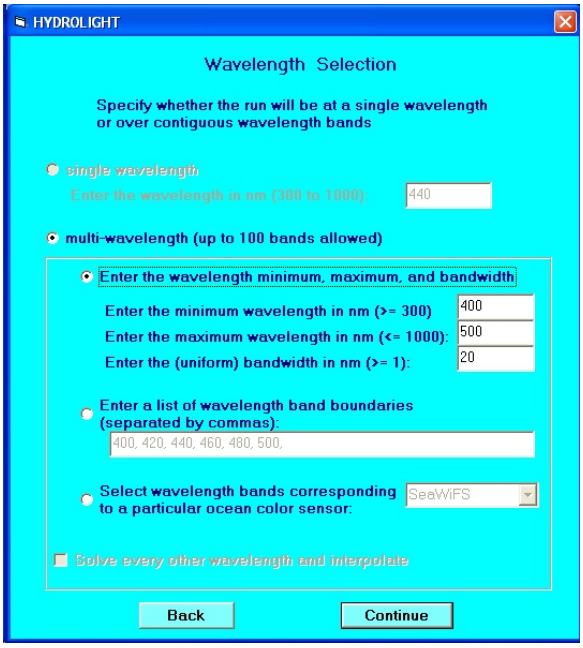
be known in order to compute the CDOM fluorescence. The same is true for Chlorophyll.

After you click CONTINUE, a notice box reminding you how the fluorescing components have been specified (earlier in the run) will appear. Note that if inelastic scatter is to be included in the run, the relevant excitation and emission wavelengths must be included (to be specified on the wavelength form). Therefore, the inelastic-scatter options are not available if you selected the ABCONST IOP model, which is for runs at only one wavelength.



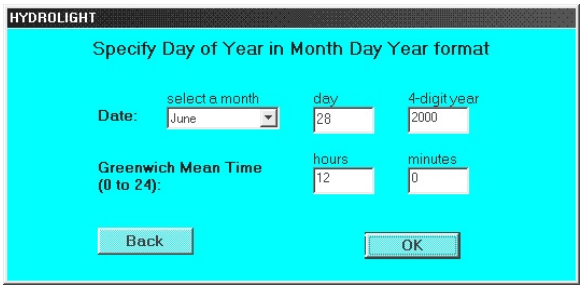
5.4 Wavelength Specification

The WAVELENGTH SELECTION form. This form allows you to select the wavelength range and bandwidths for the run. In the present example, the option of making the run at a single wavelength is not available because CDOM fluorescence was included on the previous form. Suppose that we are interested only in the 400-600 nm range. In order to include CDOM-fluoresced light that is excited in the near UV and emitted at blue wavelengths, the run should be started at 350 nm. As shown here, the wavelength bands for the run will be chosen to match the SeaWiFS sensor.



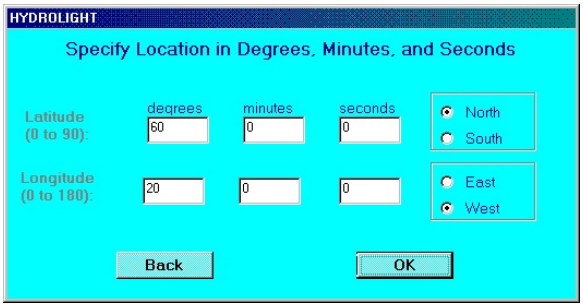
For convenience, wavebands corresponding to several ocean color sensors are provided. If uneven bandwidths are desired (e.g., to exactly match the bandwidths of a particular sensor), the band boundaries can be entered manually, e.g., 400, 410, 425, 440, 450,.... Note that HYDROLIGHT must always run with contiguous wavelength bands. For example, you cannot

of year and decimal hour of day) for time.

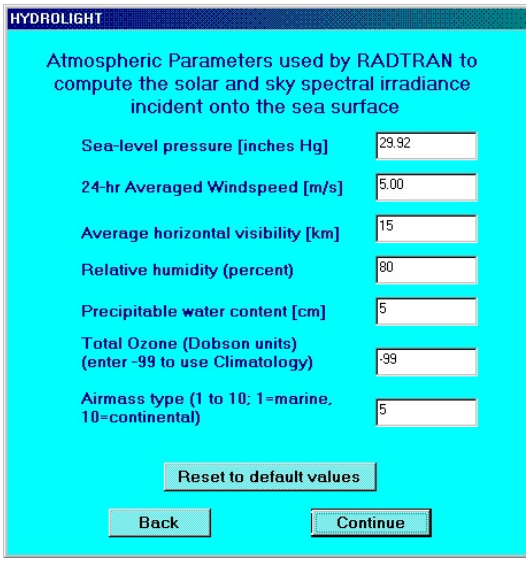


HYDROLIGHT's UI will calculate the day of the year and time in decimal format for you, if you prefer to use the month/day/year/hour/minute format. Simply click the SPECIFY TIME AS MDY... button. After you have entered the data and press continue, the UI will perform the calculations and the decimal values will be placed in the appropriate boxes on the previous form.

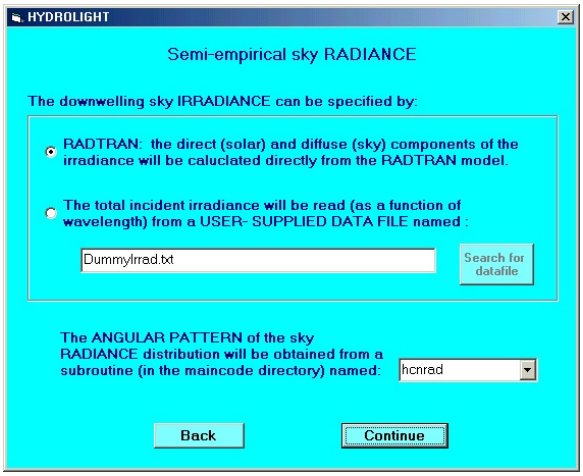
Similarly, latitude and longitude can be specified in **d**egrees, **m**inutes and **s**econds (DMS) by clicking on the SPECIFY LOCATION IN DMS button.



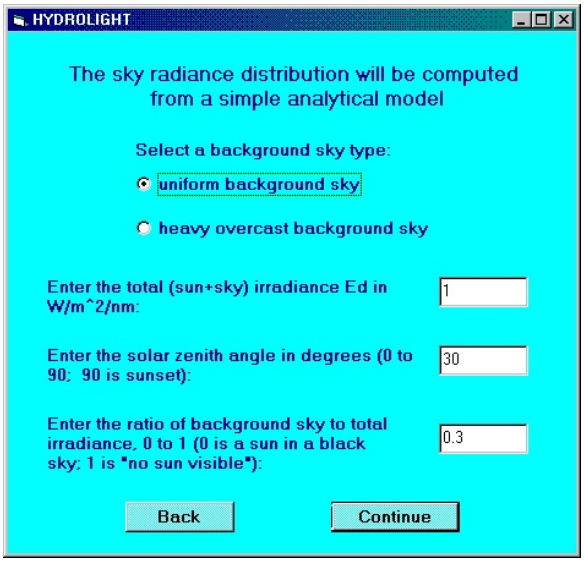
The RADTRAN ATMOSPHERIC PARAMETERS form for semi-empirical sky radiances. Users can specify various atmospheric parameters used by RADTRAN (Gregg and Carder, 1990) to calculate the irradiance at the sea surface. If not specified here, the 24-hour average windspeed will be set to be equal to the current windspeed (set in the air-water boundary form). The sky parameters will be written to the file `GCatmos.txt` to be read by HYDROLIGHT.



The SEMI-EMPIRICAL SKY RADIANCE form. The wavelength-dependent sky irradiances can be specified either from RADTRAN or from a user supplied data file. The subroutine that sets the angular pattern of the sky radiance can be specified here (the default is HCNRAD), which gives the Harrison and Coombes Normalized Radiances.



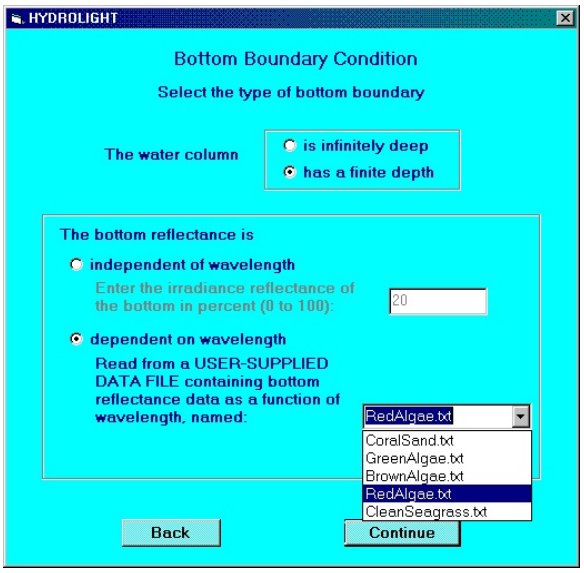
The IDEALIZED SKY RADIANCE form. This form requests the input needed by the routines on files maincode\cosirrad.f and maincode\cosrad.f which make the idealized sky radiance model (see the Technical Documentation for details). This sky radiance model is intended for radiative transfer studies that require a simple analytical model for the sky radiance distribution (such as a sun in a black sky or a heavy overcast). This sky radiance model is only available for use with single wavelength runs, since it cannot account for wavelength dependence of the sky radiance.



5.6 Bottom Boundary Condition

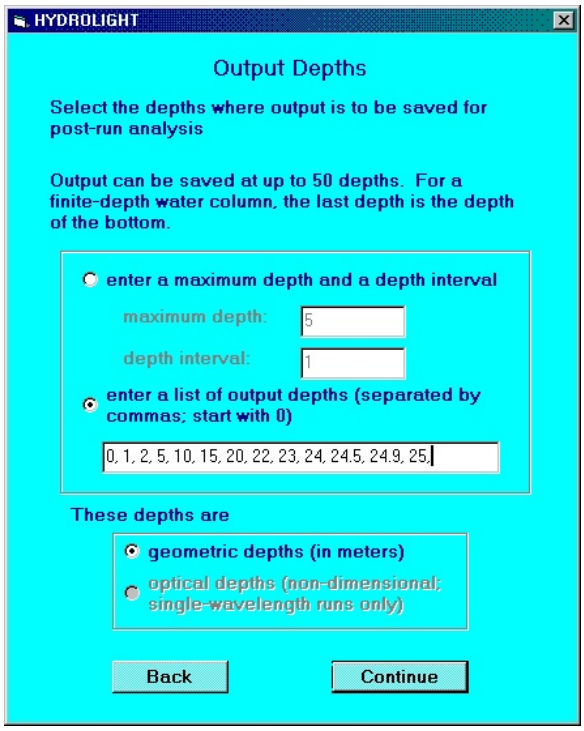
The BOTTOM BOUNDARY CONDITION form. This form requests the information needed to specify the bottom boundary condition. If the water is infinitely deep, the IOPs at the deepest depth of interest (to be specified on the output depth form) will be used to compute the

reflectance of the infinitely deep layer of water below the region of interest. If the water is finitely deep, the irradiance reflectance of the bottom must be specified. In the option shown, the pull-down menu is used to select one of the available files of user-supplied reflectance vs. wavelength data for a Lambertian bottom.



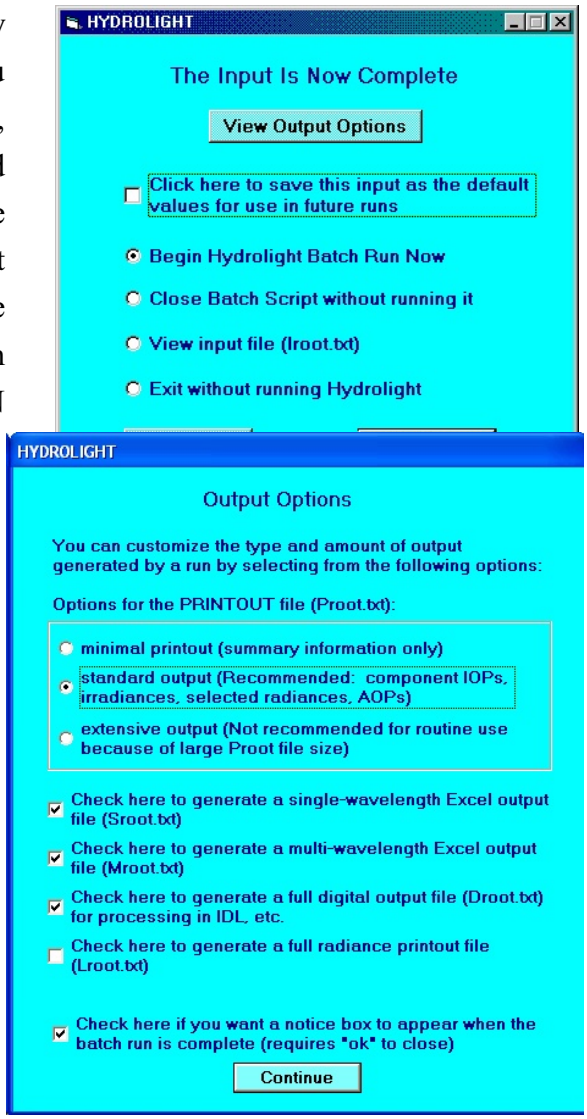
5.7 Output and Run Options

The OUTPUT DEPTHS form. This form specifies the depths at which output from the run is to be saved for later analysis. Note that *the depths as which output is to be saved in no way affects the value or accuracy of the output at a given depth.* In the example shown, output is obtained at irregularly spaced depths near the surface and near the bottom, in order to get better depth resolution of the light field behavior near the surface and the bottom boundaries. However, if output were being obtained only at depths 0, 10, 20, and 25 m, the output at those four depths would be the same, but you would not have the additional values at the other depths. Note that the option of having the listed depths be optical depths is not available in this example, because we already have chosen to have a multi-wavelength run. Users can change the maximum number of output depths in the RUN

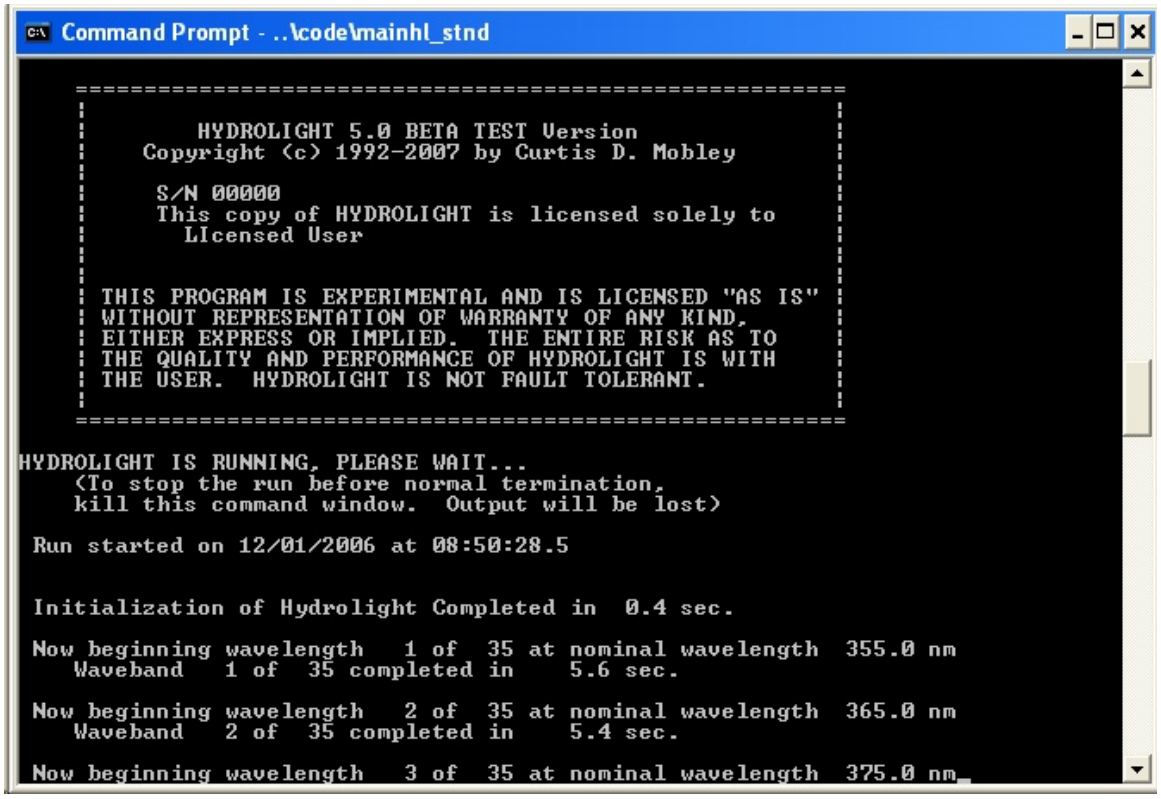


PARAMETERS form.

The FINAL form. All of the input required by HYDROLIGHT has now been obtained. If you check the CLICK HERE TO SAVE THIS INPUT box, the input you have just entered will be saved and will become the default values the next time you run the UI. This will minimize the input required, if the next run is similar to the one now being made. If you wish to add another run to this batch, click the ADD ANOTHER RUN button. If you click on continue, a command window (shown below) will be spawned and HYDROLIGHT will recompile (as necessary) and run in that window. After the command window is spawned, HYDROLIGHT is running independently of the UI. You can then click on DEFINE A NEW BATCH RUN and begin entering the input for the next HYDROLIGHT run. Note, however, that the next run cannot be started until the present run has finished. The `Iroot.txt` input file generated by the UI can be viewed and edited; this feature should only be used by advanced users who are familiar with the format of the input file (described in the Technical Documentation). Any editing of the input file cannot be stored into the default values.



The OUTPUT OPTIONS form. If the VIEW OUTPUT OPTION is selected from the FINAL form, a screen will appear giving the user several options for selecting the type and amount of output generated from a run. These values are stored as defaults and will persist with all future runs until they are changed by the user. These setting will only be stored for future runs if the SAVE THIS INPUT AS DEFAULT is selected **after** these settings are selected.



Example command window showing that HYDROLIGHT has recompiled, relinked, and is running. Time stamps provide a progress report for the run.

6. EXAMPLE HYDROLIGHT RUNS

This section briefly describes several example HYDROLIGHT runs. The input and output files for these examples are all found on the examples directory. You can reproduce these runs on your own computer and compare your output with that from the example runs to verify that HYDROLIGHT is performing correctly on your computer. The example runs were all made on a 1.8 GHz Pentium 4 processor. Run times (shown in the printout) on your computer will be longer or shorter, depending on the speed of your computer. (Note also that the "run time" given in the printout is "wall clock" time, not true computation time. Therefore, identical runs may show different run times in the printout, if the computer also was performing other tasks while HYDROLIGHT was running.) The output from your runs should be identical to that from the examples to within numerical roundoff errors, which may cause very slight differences in some output values. All of the input and output files for these example runs can be found in the HE5\examples directory.

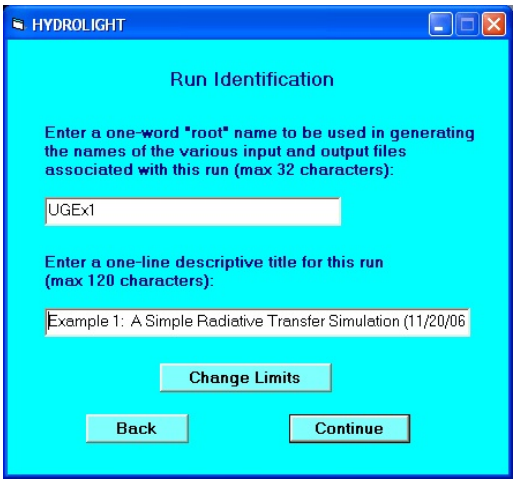
6.1: Example 1: A Simple Radiative Transfer Simulation

This tutorial will walk you through your first run of HYDROLIGHT. Each run is specified by two files: The input file (IUGEx1.txt, in this case), and the run script (RUGEx1.bat). The various input and output files for this run can be found in the ..\examples\Example1 directory.

This example illustrates running HYDROLIGHT in a manner that is often used in idealized radiative transfer studies. This example solves the monochromatic RTE for a homogeneous, infinitely deep water body. For pedagogic purposes, suppose that we wish to define the inherent optical properties of the water body by the phase function and the albedo of single scattering, $\omega_o = b/c$. Here $c = a + b$ is the beam attenuation coefficient. We shall use $\omega_o = 0.75$ along with a one-term Henyey-Greenstein scattering phase function with an asymmetry parameter of $g = 0.9$. The output will be requested at various optical depths ζ, as is customary in radiative transfer studies.

To begin, double-click on the HYDROLIGHT icon on your desktop that you made during installation (or double click HE5WinUI.exe in the HE5\Frontend directory). To make sure you have a "clean slate" click the RESET defaults button on the first screen. You will need to read the license agreement and understand the disclaimer before you may CONTINUE.

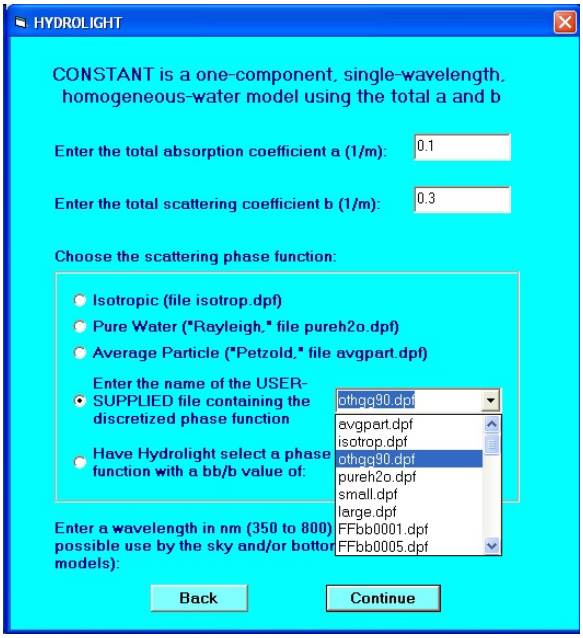
The next screen you see will be the Run Identification screen. For this example, the root name is UGEx1 (for Users' Guide Example 1). After entering a root name and run title, click CONTINUE.



A screen will pop up showing you the names for the various output files. Note that the name is always made by adding a letter to the front of the selected rootname. Click OK.

This run is made by selecting the constant IOP model. Select CONSTANT and press CONTINUE. You will not get the message box described earlier reminding you that you have "changed your IOP model" and will need to check your options carefully. Hit CONTINUE.

Next, you will get a screen asking you to specify the IOPs for this run. The input for this model needs a and b, not ω_o. However, we can use *any* values for a and b that give the desired value for ω_o, because we are requesting the output as a function of optical depth. The actual values of a and b are relevant only if we wish to convert optical depth to geometric depth via $z = \zeta/(a + b)$. Therefore, let us use $a = 0.1$ m^{-1} and $b = 0.3$ m^{-1}, which give $\omega_o = 0.3/(0.1 + 0.3) = 0.75$.

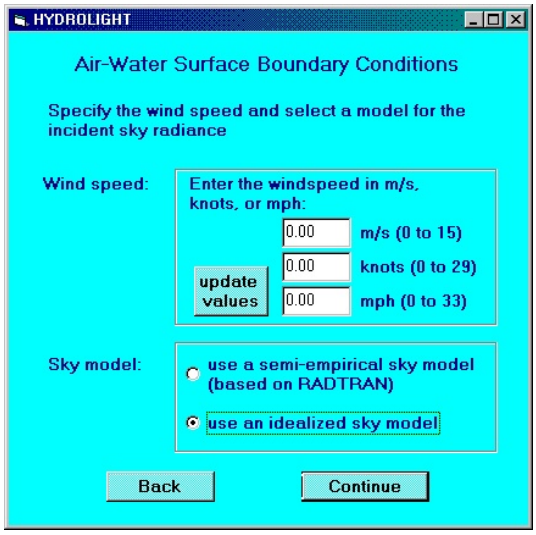


The desired phase function is found on file othgg90.dpf, which is one of the example discretized phase functions supplied with HYDROLIGHT (othgg90 = One-Term Henyey-Greenstein phase function with g=0.90; this phase function was created via a special run as described in the Section 4.1 of the Technical Documentation). Since this model can only be run in a single-wavelength mode, we can specify our wavelength here to be 550 nm (may

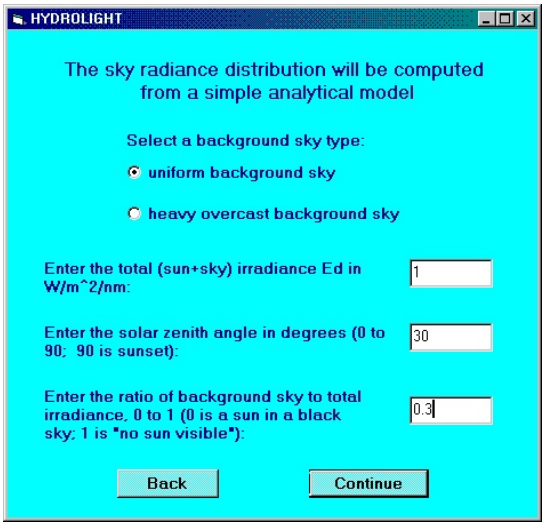
be used by sky model or if we use a spectrally-dependent bottom reflectance). Hit CONTINUE.

The next form will give us the opportunity to include bioluminescence in this run. Note that the various forms of inelastic scattering are "greyed out" since they require a multi-wavelength run and we are solving a monochromatic case. Do not include bioluminescence and hit CONTINUE.

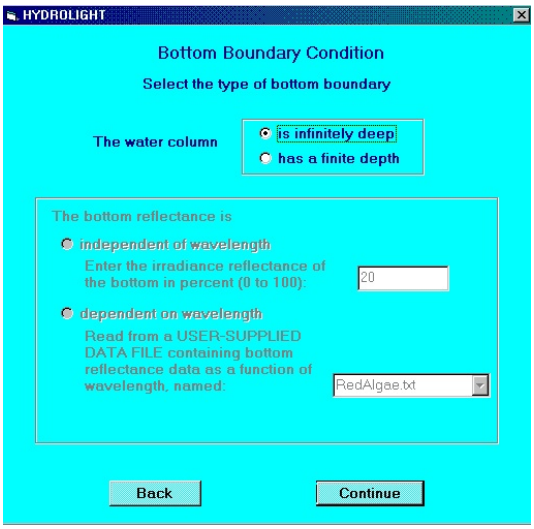
For this example run select a level surface (wind speed = 0 m/s). The wind speed is displayed in three units of measure. Note: you do not need to click UPDATE every time you change the wind speed. The wind speed is converted to m/s (if needed) and the values updated when you leave this form. Hit CONTINUE.



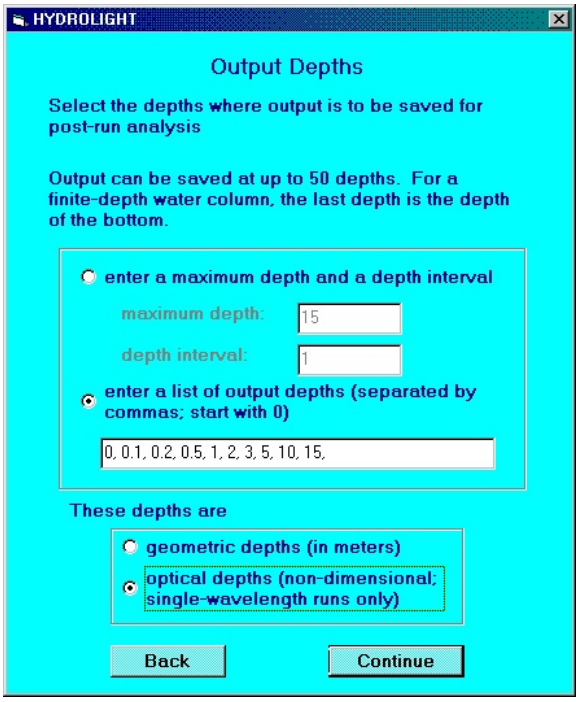
Select a uniform sky with a total downwelling irradiance E_d of 1.0 W m^{-2} nm^{-1}, the sun at a 30 degree zenith angle, and a diffuse-to-direct irradiance ratio of 0.30. Click CONTINUE.



In this example, select the water to be infinitely-deep. Hit CONTINUE.



For this run we will solve the monochromatic RTE to $\zeta = 15$ with irregularly-spaced output depths. Since we want to solve our problem in terms of optical depth (ζ) rather than geometric depth (meters), select the OPTICAL DEPTH option at the bottom of the page. This option is only available with monochromatic runs. Hit CONTINUE.



We have now provided HYDROLIGHT with all the information it needs to make the run. From this form you can choose to save your input for future runs. For instance, you might want to process several data files or vary some parameters to study their effects. You can also view and change your printout options.

Select the RUN HYDROLIGHT NOW option and click CONTINUE.

An MS-DOS command window when HYDROLIGHT begins running. This HYDROLIGHT run took 4.4 seconds on a 1.8 GHz Pentium 4 processor. If you select RUN ECOLIGHT NOW, you can make the same run using the ultra-fast, azimuthally-averaged code. The ECOLIGHT run took 0.2 seconds. Once the MS-DOS window appears, you are free to return to the ID form and begin specifying your next run. However, do not begin (by selecting RUN NOW from the final form) your next run until the previous one has finished.

As an example of the type of output that can be obtained from HYDROLIGHT, Fig. 6 shows how various K functions approach the asymptotic value K_∞. This plot was generated by the IDL routine ugfig6.pro, which is found in the examples\IDL directory. Routine ugfig6.pro read the file Dugex1.txt (in the \output\digital\ directory) as input. Because this run was made in terms of optical depth, the K functions have been plotted as non-dimensional quantities: K(non-dimen) = K(dimen)/c; see Note 3 below.

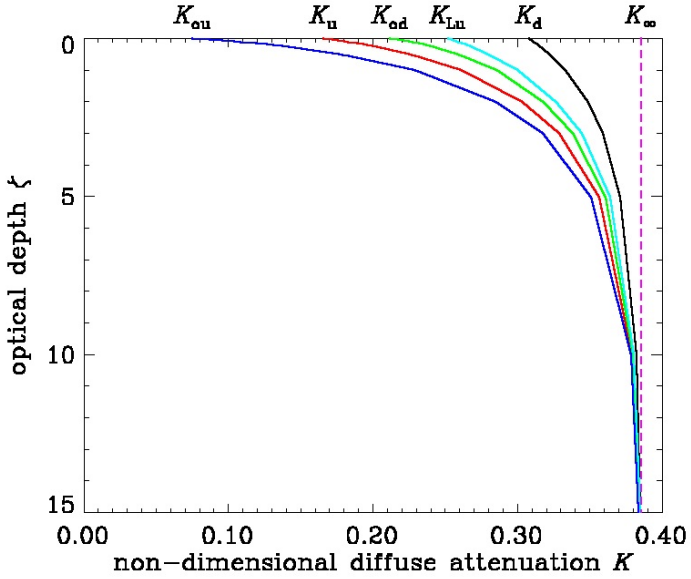


Fig. 6. Selected non-dimensional diffuse attenuation functions, as computed by the HYDROLIGHT run of Example 1.

Note 1. The abconst IOP model is for runs at a single wavelength, which was taken to be 550 nm. However, the wavelength is irrelevant in this run, because the run used the idealized sky

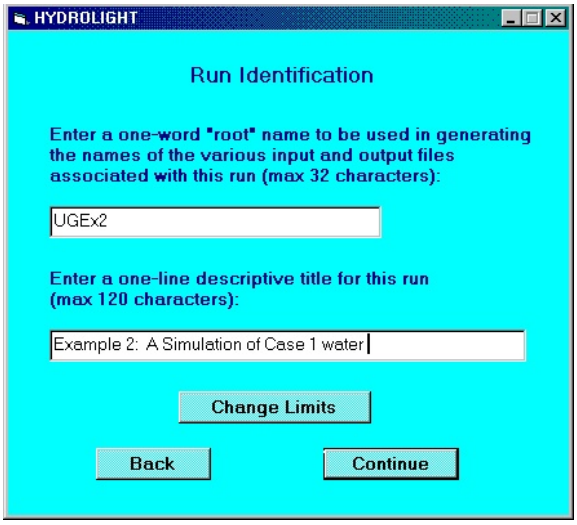
model and had infinitely deep water. Had the run used the semi-empirical sky model or had it used a finite-depth bottom with a wavelength-dependent bottom reflectance, the wavelength would have been needed. Because the run was at a single wavelength, there was no option of including inelastic-scattering.

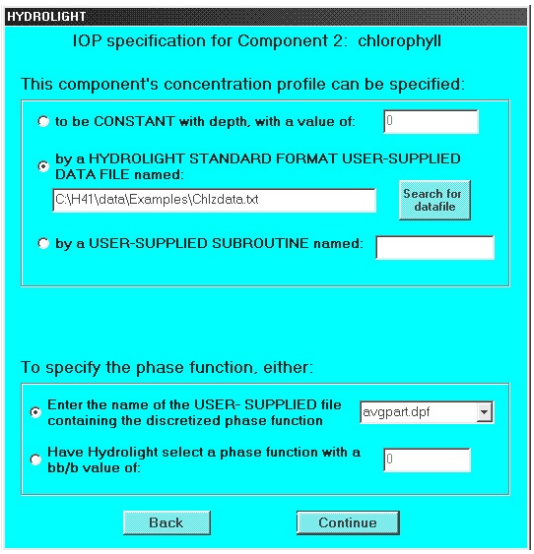
Note 2. For the values of $a = 0.1$ m^{-1} and $b = 0.3$ m^{-1} used in this run, 15 optical depths corresponds to $15/c = 37.5$ m of geometric depth. If you make another run with, say, $a = 1.0$ m^{-1} and $b = 3.0$ m^{-1} (and all else the same), you will find that the radiances and irradiances are all the same as a function of optical depth, even though 30 optical depths is then 3.75 m. Moreover, the run times will be the same, which is consistent with the comments below.

Note 3. Even though the run saved its output at the specified optical depths, the *K* functions in the default printout were computed using geometric-depth derivatives; the *K* functions therefore have units of inverse meters, as is customary. If you want non-dimensional *K* functions computed with optical-depth derivatives, you can multiply the values in the printout by $1/c$ (= 2.5 m in the present case). Routine maincode\kfcn.f, which computes the *K* functions, also has the option of printing out a table of non-dimensional *K* functions. Note also that the dimensional *K* functions will be different for the $(a,b) = (0.1,0.3)$ and (1,3) runs even though the non-dimensional *K* functions (computed using optical-depth derivatives) are the same at corresponding optical depths.

6.2: Example 2: A Simulation of Case 1 water with the Classic IOP Model

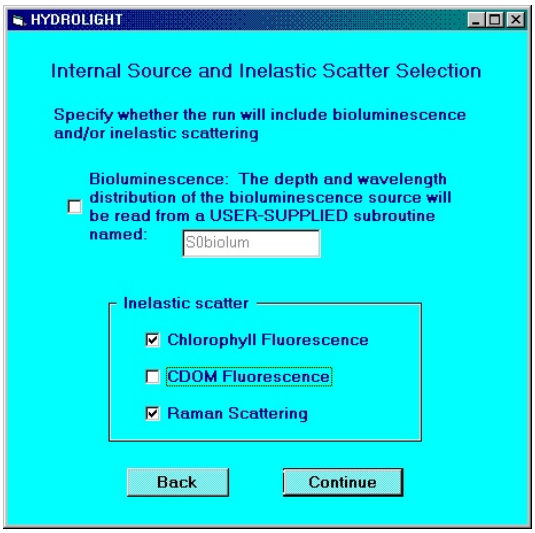
Now that you have made your first run of HYDROLIGHT, let's consider a multi-spectral Case 1 water simulation. The various input and output files for this run can be found in the ..\examples\Example2 directory. In this case, the root name for this run is UGEx2. After you have entered the root name and a run title, hit CONTINUE. When the informative page pops up listing the various file names for this run, hit CONTINUE.





For the second component, chlorophyll-bearing particles, you will need to specify the concentration profile and the phase function. Click on the SEARCH FOR DATAFILE button and browse until you find the file chlzdata.txt in the Examples subdirectory (or the Data directory in the HYDROLIGHT folder).

Next you need to specify the phase function for this component. Select the data file option and use the pulldown menu to select Petzold's average-particle phase function file, avgpart.dpf. Hit CONTINUE. A notice will appear informing you that the the data file chlzdata.txt will be read.



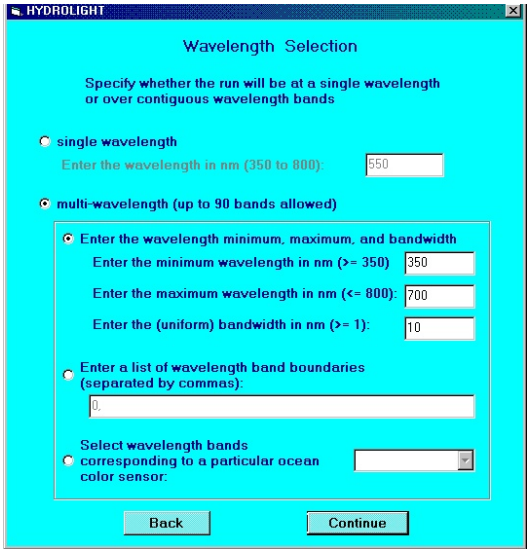
Next, you will need to decide whether to include any inelastic scattering (fluorescence) or sources in the run. Check the chlorophyll fluorescence and Raman scattering boxes. Then hit CONTINUE.

Note that if you had decided to include bioluminescence, you would have been prompted to provide information on the bioluminescence by an additional form. If you had included CDOM fluorescence, the absorption of CDOM will be apportioned based on the bio-optical model and a set fluorescence efficiency (set in setdflts.f) will be applied.

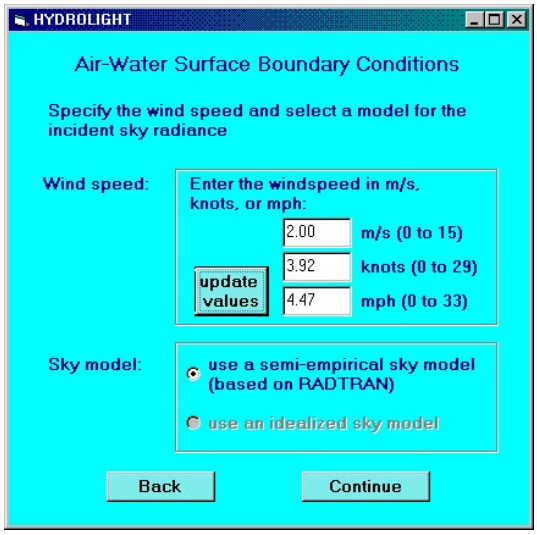
A notice will appear telling you where HYDROLIGHT plans on getting information on the component concentrations needed for the chlorophyll fluorescence. As the notice says, remember to always include the excitation wavelengths if you want to include inelastic scattering in a run!

Next, we need to select the wavebands for the run. Since we have selected fluorescence and inelastic scattering we are not allowed to select the single-wavelength option.

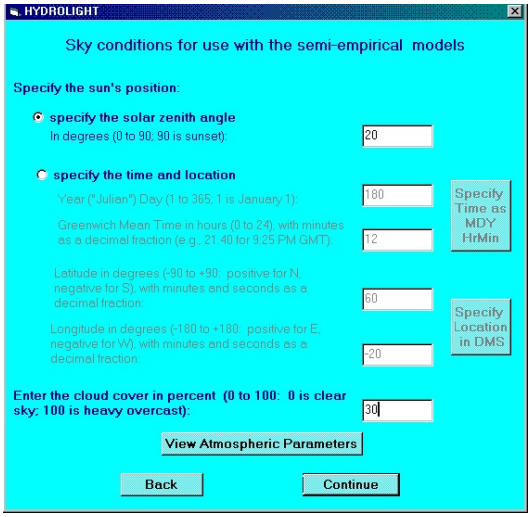
In a multi-wavelength run you have a few options for how you specify the wavebands. For this run, select the "min/max/interval" option and set the run to go form 350 nm to 700 nm with 10 nm wide bands. Hit CONTINUE.



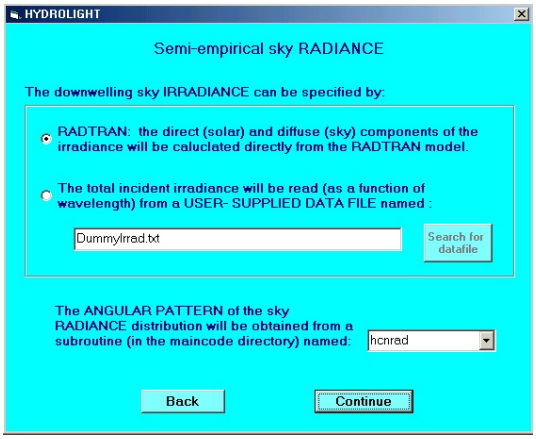
Set the wind speed to 2 m/s. Click the UPDATE button to see how many knots this is. Since we are making a multi-wavelength run, we must use the semi-empirical sky model. Press CONTINUE.



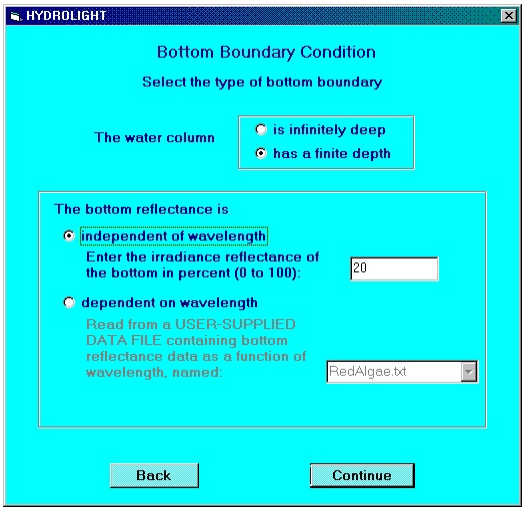
For this run, set the sky conditions so that the sun has a zenith angle of 20 degrees and we have 30% cloud cover. Don't forget that you can view (and change) the atmospheric parameters — but leave them at their preset values for this run. Press CONTINUE.



We will use RADTRAN to calculate the irradiance for our given atmosphere and sky conditions and use the Harrison and Coombes normalized sky radiance model to specify the distribution of sky radiance (by selecting the subroutine hcnrad). After selecting these options, click CONTINUE.

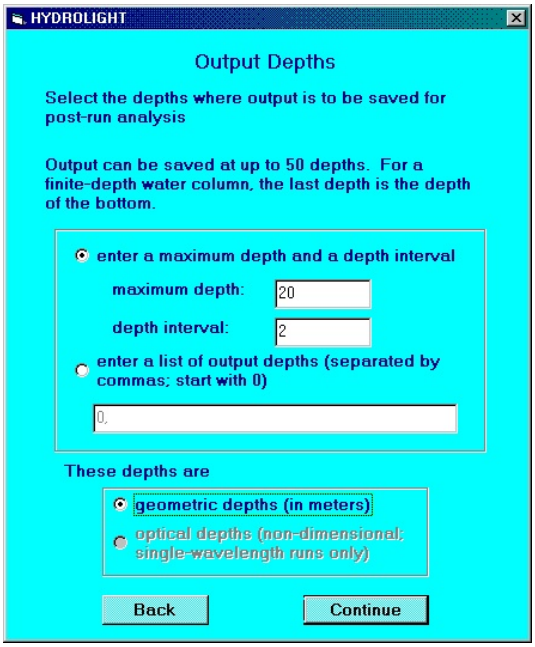


Select the finite depth bottom condition option and set the bottom reflectance to be 20%, independent of wavelength (an approximation for "gray mud"). Click CONTINUE.



The sea floor will be placed at the maximum output depth selected on this form. If we had selected an infinitely-deep bottom, the IOPs below this depth would be assumed constant with the value at this depth. Select a maximum depth of 20 meters with output every 2 meters. We must use geometric depths since we are making a multi-wavelength run.

Don't forget that the accuracy of the calculations will not be affected by the number or locations of output depths! Hit CONTINUE.



We arrive at the same final form as before, having provided HYDROLIGHT with all the information it needs to make a run. The three files specifying this run are: The input file (IUGEx2.txt), the run script (RUGEx2.bat), and a FORTRAN file containing the appropriate subroutine calls for this run (incfiles.for in the maincode directory). Select the RUN HYDROLIGHT NOW option and click CONTINUE. This run took 2 minutes on a 1.7 GHz Pentium 4.

As an example of the type of output that can be obtained from HYDROLIGHT, Fig. 7a shows the remote-sensing reflectance $R_{rs} = L_w / E_d$ (where L_w is the water-leaving radiance, i.e., the total radiance minus the reflected sky radiance; and E_d is evaluated just above the water surface). In this example, R_{rs} is greatest at near-UV and blue wavelengths, which is expected for Case 1 water with a chlorphyll concentration ~ 0.5 mg/m^3. Note that HYDROLIGHT computes the water-leaving and reflected-sky radiances separately, so the remote-sensing reflectance shown here is exact, not an approximation obtained via any semi-empirical correction for reflected-sky radiance or for transmitted upwelling radiance from below the surface.

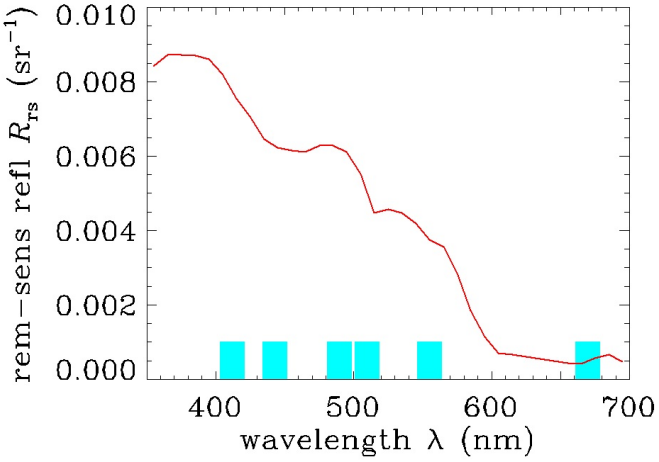


Fig. 7a. The remote-sensing reflectance as a function of wavelength for the CLASSIC Case 1 water of Example 2. The shaded bars at the bottom of the figure show the nominal SeaWiFS sensor bands. (This figure was generated by IDL routine ugfig7n.pro.)

6.3: Example 3: A Simulation of Case 1 water with a NEW IOP Model

Some features of the Classic Case 1 model are over 20 years old and. Version 5 contains a new Case 1 IOP model based on recent bio-optical modeling. The new model is described in the Technical Document. For this example, we will select the NEW Case 1 IOP model but otherwise keep everything the same as in the previous example. Select the "medium UV Chlorophyll specific absorption" option (only affects wavelengths < 400nm). Note that the

phase function is automatically set based on the ratio of small to large particles, which is a function of the chlorophyll concentration. Figure 7b shows the resulting remote-sensing reflectance.

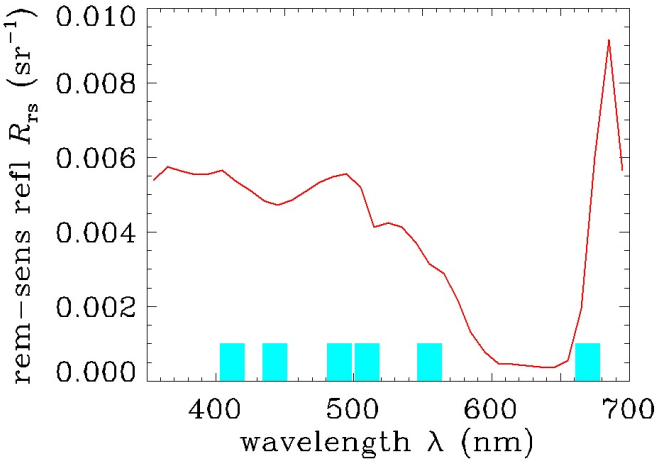


Fig. 7b. The remote-sensing reflectance as a function of wavelength for the NEW Case 1 water of Example 3. The shaded bars at the bottom of the figure show the nominal SeaWiFS sensor bands. (This figure was generated by IDL routine ugfig7n.pro.)

6.4: Example 4: A Simulation of Case 2 Water

As a more complicated and oceanographically relevant example of running HYDROLIGHT, consider a simulation the light field in shallow Case 2 water. The water was modeled as a four-component system:

- Component 1: pure water
- Component 2: chlorophyll-bearing particles (with NO covarying yellow matter)
- Component 3: CDOM (yellow matter) that does *not* covary with the chlorophyll concentration
- Component 4: mineral particles that do *not* covary with the other components.

The corresponding *ab* routine is found on file abcase2.f. Since several methods of specifying concentration and component IOP models are available, this "ab" routine provides a good starting place for studying Case 2 water. Also, abcase2.f can be used as a template for users to develop their own four-component models (see Technical Documentaion for instructions on developing code for new "ab" models).

To make this run, start HYDROLIGHT as before, provide a root name and run title and select

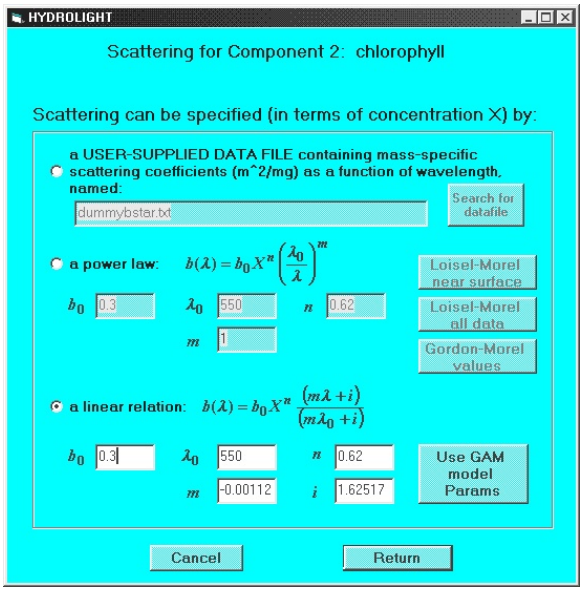
the ABCASE2 option from the IOP model form. After you see the form reminding you about the four components in this model, you will be taken through a set of forms to specify the IOPs for each of the four components. Since there is considerably more freedom with the Case 2 water model, you will find there is more information you will need to provide and hence, more buttons on some of the component forms. Going though the forms, specify the components as follows:

- Component 1: pure water

  For pure water you will need to specify the pure water absorption and the phase function. For the absorption, select the Pope and Fry option. The pureh2o.dpf scattering phase function will be used.

- Component 2: chlorophyll-bearing particles

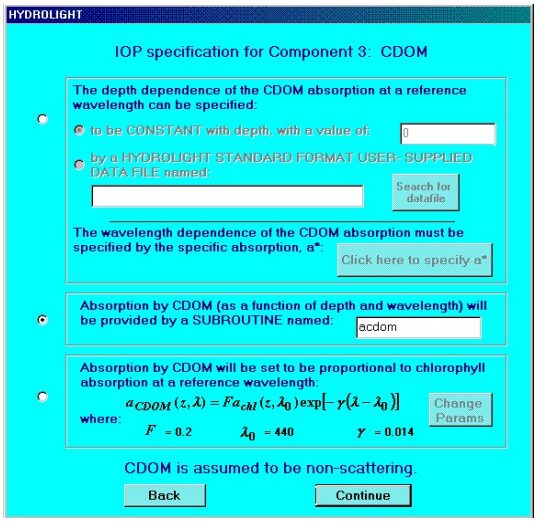
  For Component 2 you will need to specify concentration, specific absorption and scattering models, and the scattering phase function. In this example, specify the concentration by specifying the subroutine named *chlzfunc*.



Select the "chlorophyll-based Case 1 water model" for absorption. Select the linear scattering model with the default values (hit the USE GAM MODEL PARAMS button) and set b_0 to 0.30. Select ffbb005.dpf (Fornier-Forand with a b_b/b ratio of 0.005, or 0.5% backscatter) as the scattering phase function.

The subroutine on file chlzfunc.f defines a depth-dependent chlorophyll profile. The chlorophyll concentration for this run increased from roughly 1.2 mg m^{-3} at the surface to 5.0 mg m^{-3} at z = 5 m, and then decreased to 2.3 mg m^{-3} at z = 8 m.

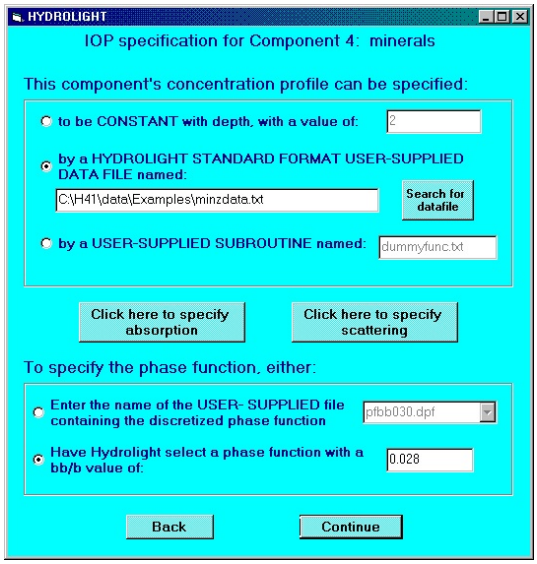
- Component 3: CDOM
  In this run, CDOM absorption will be provided by calls to the subroutine aCDOM in file acdom.f.



The routine on file acdom.f defines a CDOM absorption coefficient that depends on depth and wavelength. At 440 nm, the absorption by CDOM was 0.1 m^{-1} at the surface; this value decreased exponentially to 0.02 m^{-1} at 8 m (to crudely simulate a near-surface layer of CDOM as might arise from river input). The CDOM absorption decreased exponentially with wavelength; it was negligible at red wavelengths, but was triple the above values at 350 nm.

Note that there is an option to select CDOM to covary with chlorophyll with the form of the Prieur-Sathyendranath-Morel Case 1 water model. This covarying CDOM is automatically included in the ABCASE1 model of the previous example, but ABCASE2 explicitly separates the chlorophyll and CDOM components and allows the user to set the three co-vary parameters.

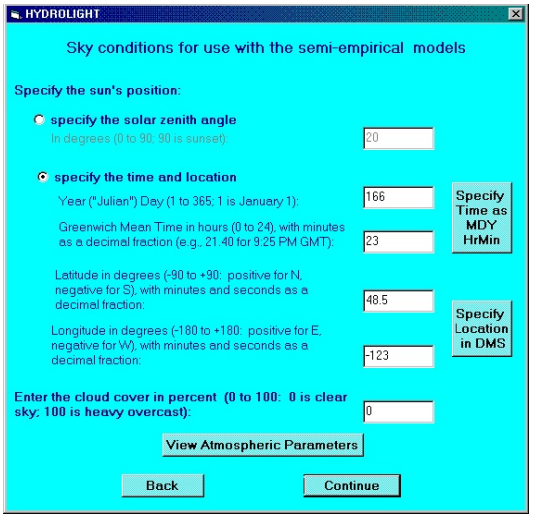
- Component 4: minerals
  The mineral in this run will be treated as red clay particles.



The concentration will be provided by the data file minzdata.txt in the ..\data\Examples\ directory, which crudely simulates a layer of resuspended sediment. The specific absorption and scattering coefficients will be provided by the data files..\data\defaults\astarmin_redclay.txt and ..\data\defaults\bstarmin_redclay.txt, respectively. Have HYDROLIGHT choose a phase function (Fournier-Forand) with a backscattering ratio of 2.8% (b_b/b = 0.028).

Include Raman scattering and fluorescence by chlorophyll and CDOM on the inelastic form

and select the wavebands to match those of SeaWiFS. Note that the first SeaWiFS wavelength band is 402-422nm. Raman scatter and CDOM fluorescence are excited by wavelengths shorter than 400nm, so there will be some inaccuracy in the inelastic-scatter calculations, but this will be a minor effect for this water body. Select a wind speed of 4 m/s.



Use the "semi-empirical" sky model with a year day of 166, latitude of 48.5 degrees North, longitude of 123 degrees West, and Greenwich mean time of 23 hours (which correspond to mid-afternoon on June 15 in Puget Sound, Washington, USA; the corresponding solar zenith angle was 41.55°). The solar azimuthal angle relative to the downwind direction is (by default) 0°. Assume that the sky was clear.

Take the water column to have a finite depth with a sea floor of green algae (wavelength-dependent reflectance) at a depth of 8 meters and have output printed at 0.5m intervals. This should give you everything you need to make this run!

Depending on the depth and wavelength, the total absorption was dominated by water, by pigmented particles, by CDOM, or by mineral particles. Scattering by particles was always much greater than scattering by the water; the CDOM was assumed to be non-scattering. This model for a and b gave albedos of single scattering, ω_o, that ranged from almost zero (at 765 nm, where absorption by the water is very high) to more than 0.85 (near 570 nm, where absorption was lowest). The geometric depth of 8 m corresponded to over 13 optical depths at 350 nm (where both CDOM absorption and particle scattering were high) and to less than 8 optical depths near 570 nm.

This run required 80 seconds on a 1.7 GHz Pentium 4 Processor. It should be noted that the simulation required the solution of the radiative transfer equation for 20 wavelength bands, with three types of inelastic scattering connecting the bands. On average, each wavelength solution was taken to about ten optical depths. Thus the run time corresponds to about four seconds per wavelength per optical depth. The archival printout file PUGEx3.txt is less than half a Mbyte, but the digital output file DUGEx3.txt (which contains the radiance distribution at all depths, directions, and wavelengths) is about 7 Mbytes.

The following figures show some of the input to and output from this simulation. The IDL

plot routines that generated these figures are found on the IDL directory. Figure 8 shows the total IOP's (sum of all four components) a, b, and ω_o as functions of depth and wavelength. (This figure was generated using IDL routine ugfig8.pro.)

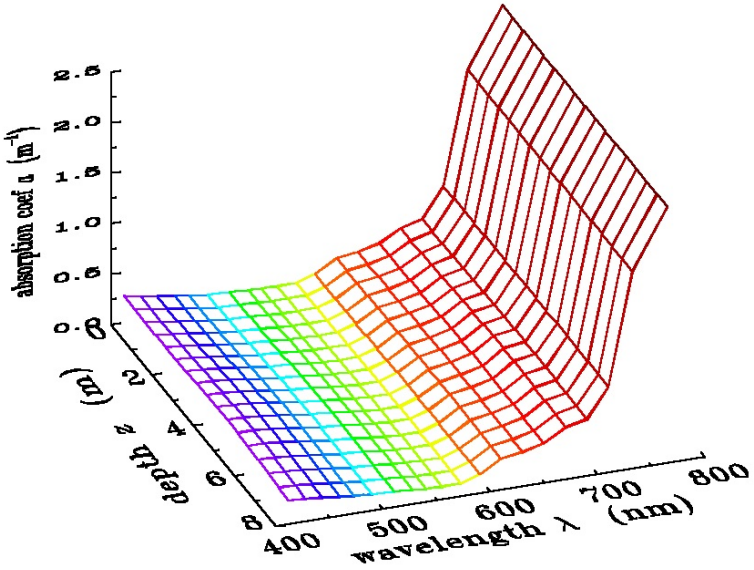


Fig. 8(a). The total absorption coefficient a as function of depth and wavelength, as used in Example 4.

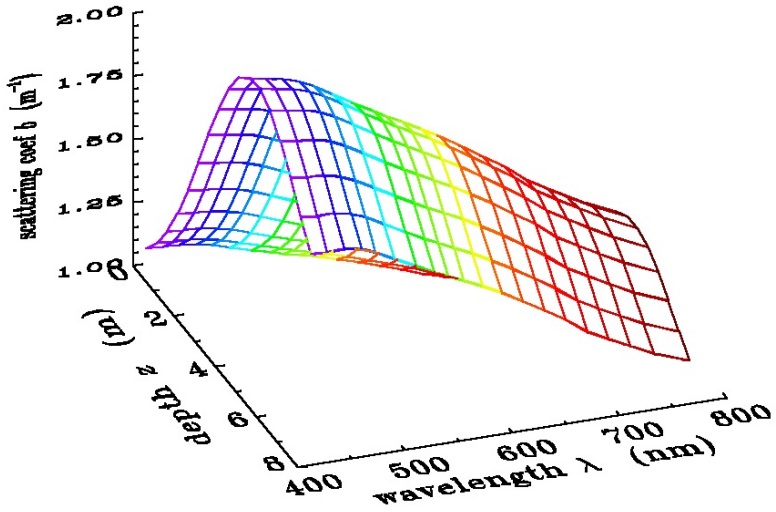


Fig. 8(b). The total scattering coefficient b as function of depth and wavelength, as used in Example 4.

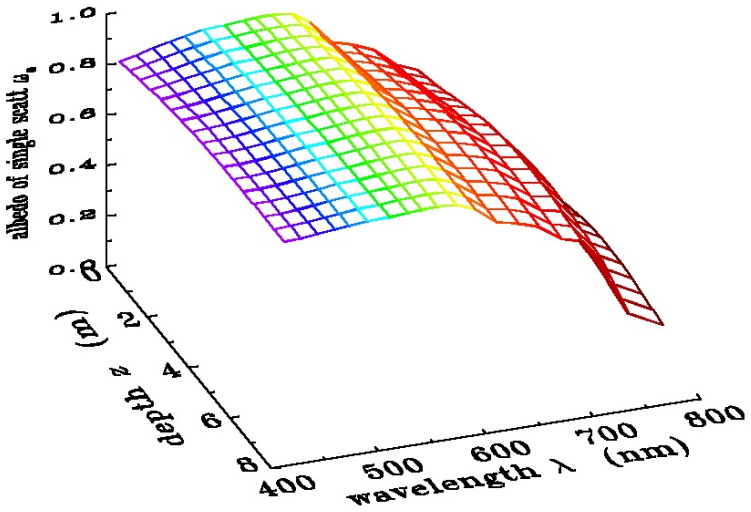


Fig. 8(c). The total albedo of single scattering ω_o as function of depth and wavelength, as used in Example 4.

Figure 9 shows how the radiance distribution in the azimuthal plane of the sun changes with depth, polar angle, and wavelength. (This figure was generated using IDL routine ugfig9.pro.)

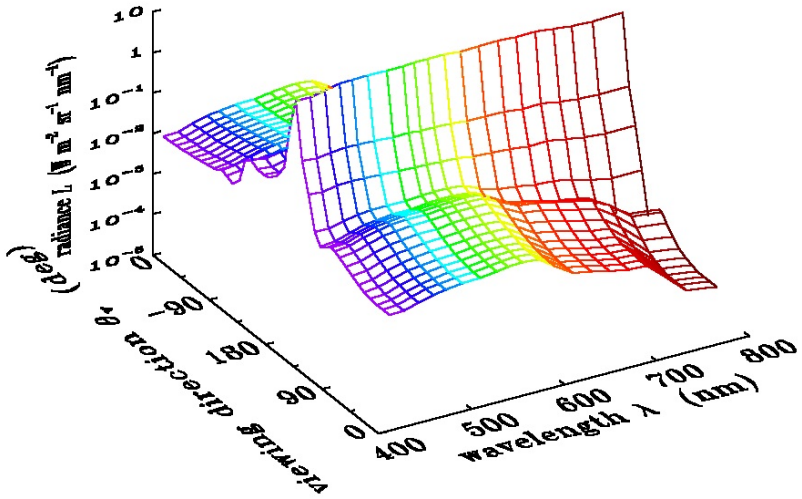


Fig. 9(a). The radiance distribution in the plane of the sun's rays, as a function of viewing direction and wavelength, at depth z = 0, which is just beneath the air-water surface. Note that the radiance axis is logarithmic. The small "bump" in the upwelling radiance at 685nm is due to chlorophyll fluorescence.

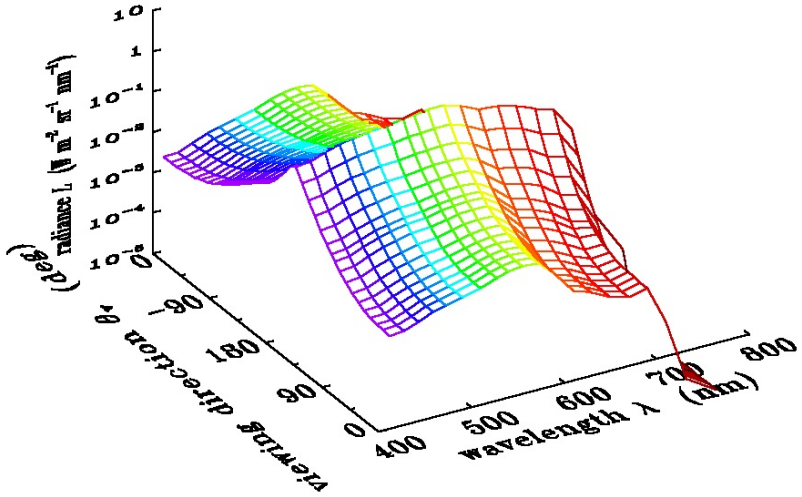


Fig. 9(b). The radiance distribution in the plane of the sun's rays, as a function of viewing direction and wavelength, at the mid-water depth of 4 m.

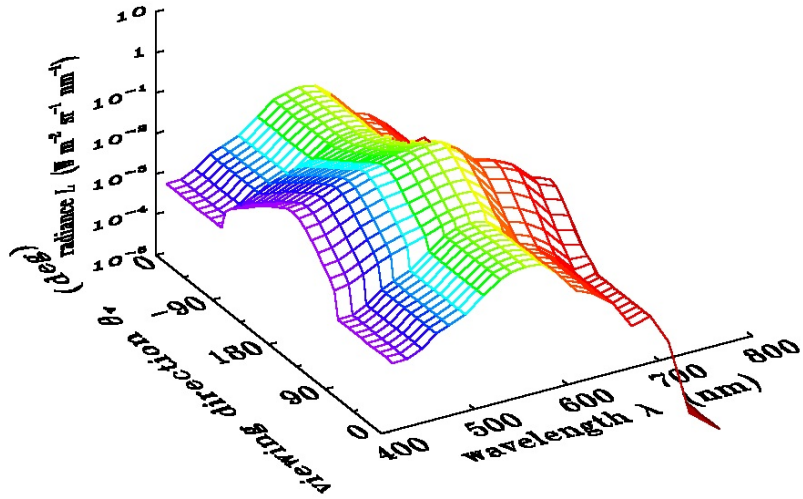


Fig. 9(c). The radiance distribution in the plane of the sun's rays, as a function of viewing direction and wavelength, just above the sea floor at a depth of 8 m. The constant radiance in the upward directions (viewing angles less than 90 deg) is a consequence of the Lambertian bottom.

Fig. 10 shows the remote-sensing reflectance $R_{rs} = L_w / E_d$ (where L_w is the water-leaving radiance, i.e., the total radiance minus the reflected sky radiance; and E_d is evaluated just above the water surface). As expected for this "green" Case 2 water, R_{rs} is greatest at yellow-green wavelengths. (Compare this with that for the "blue" water simulation of Example 2, Fig. 7a.) The bump at 685 nm shows the effect of chlorophyll fluorescence.

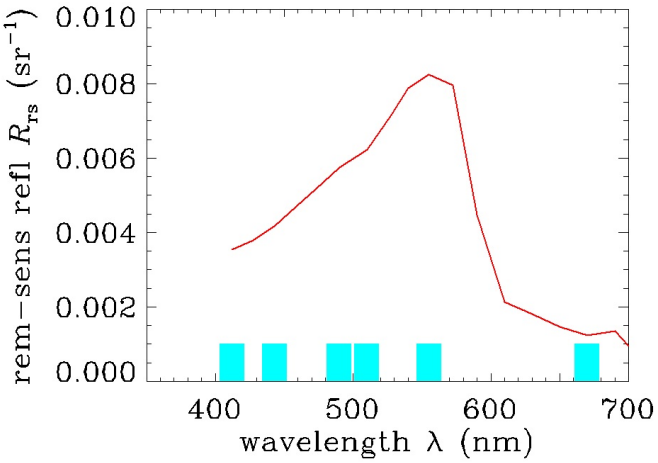


Fig. 10. The remote-sensing reflectance as a function of wavelength for the Case 2 water of Example 4.. The bars at the bottom of the figure show the nominal SeaWiFS sensor bands. (This figure was generated by IDL routine ugfig7n.pro.)

7. OUTPUT FROM STANDARD RUNS

The three examples just discussed showed example graphical output obtained by using IDL to plot data in the digital output files. Now, we will discuss the different forms of output and what is included in each.

7.1 The Default Printout

Every standard HYDROLIGHT run generates an ASCII file of "printout" (the Proot.txt file in the printout directory) that is designed to be viewed with a text editor (or word processor). This file shows, in an easily read format, information such as

- The absorption, scattering, backscattering, and attenuation coefficients for each component of the IOP model
- The atmospheric parameters used in the sky radiance model
- Various irradiances (upward and downward scalar and plane irradiances)
- Radiances in selected directions (upward, downward, and horizontal at selected azimuthal directions relative to the sun's position)
- Various apparent optical properties (mean cosines, reflectances, and diffuse attenuation functions)
- Quantities of interest in ocean-color remote sensing (incident and reflected sky radiance, water-leaving radiance)
- Any error messages generated during the run

Where appropriate, these quantities are tabulated at the user-defined depths where output was saved. The same information is repeated for each wavelength band.

It is strongly recommended that you always take a look at the printout after a HYDROLIGHT run terminates. This is easily done by opening the file with NotePad or WordPad; you can also use a word processor such as Microsoft Word® or WordPerfect® to view the file. Scan the input to make sure it was what you intended. Inspect the output to see if it looks physically plausible. If you see something peculiar in the output, try to figure out the cause—incorrect input, lack of intuition on your part about underwater light fields, or (perish the thought) a bug in HYDROLIGHT. For some purposes, it may be convenient to copy output from the default printout and paste it into graphics or spreadsheet software for further analysis.

The default printout gives a reasonable amount of information for most users. You can obtain more or less printout by selecting a different option in the Printout form of the UI (accessible from the FINAL form by selecting VIEW OUTPUT OPTIONS).

Note 1. The depths shown in the default printout may cause confusion. When you specify the depths where output is to be saved, HYDROLIGHT automatically adds a second depth just below each depth you specify. These pairs of closely spaced depths are used to compute diffuse attenuation functions (*K* functions) by the appropriate finite difference approximation to the definition. For example, K_d, the diffuse attenuation coefficient for downwelling plane irradiance E_d, is estimated from

$$K_d \doteq -\frac{1}{E_d}\frac{dE_d}{dz} \approx -\frac{1}{0.5\,[E_d(z_k) + E_d(z_{k+1})]}\,\frac{E_d(z_{k+1}) - E_d(z_k)}{z_{k+1} - z_k}.$$

The value of K_d so computed is the *average* value of K_d over the depth range z_k to z_{k+1}. However, the finite-difference approximation is an accurate estimate of K_d *at the midpoint* $\frac{1}{2}(z_k + z_{k+1})$ only if the two depths z_k and z_{k+1} are "close together," even if the irradiances are computed with perfect accuracy. Therefore, for example, if you requested output to be saved at depths $z = 0$, 1, and 5 meters, HYDROLIGHT will actually compute and save the radiance and irradiances at depths z = 0.00, 0.01, 1.00, 1.01, 5.00, and 5.01 meters. The pairs (0.00,0.01), (1.00,1.01), etc. are used to estimate the depth derivatives. However, the printout is given only at the depths you requested, namely 0, 1, and 5 meters in this example (these are the odd-indexed depths z_1, z_3, ... The even numbered depths z_2, z_4, ... are used internally only for computing *K* functions and are not shown in the printout). Since the depth index is included in some of the printout, these extra depths sometimes make the printout appear to be at every other depth (at the odd depths). The above example depths of 5.00 and 5.01 meters are used if the water column is infinitely deep with the last requested output depth being 5.00 m. If the water has a finite depth of 5.00 m, the last pair of depths is 4.99 and 5.00 m, in order that the bottom boundary be at exactly the requested 5.00 m depth.

Table 1 shows an example of the default printout for the irradiances and mean cosines. Note also that both the optical depth ζ ("zeta" in the printout) and the geometric depth *z* (in meters) are shown in the printout. Values in the air, just above the sea surface, are also shown where appropriate. Table 2 shows the corresponding printout for various *K* functions. The closely spaced pairs of depths (z_k, z_{k+1}) are shown in the printout as (z_{upper}, z_{lower}). The small

increment used in computing derivatives, which is 0.01 m by default, is set in the routine maincode\setdflts.f. Picking depths only 0.01 m apart exceeds the ability of oceanographic instruments to measure the corresponding changes in the light field, but such closely spaced values gives excellent depth resolution of *K* profiles in the numerical model.

Irradiances (units of W/m^2 nm), Mean Cosines (Mubars), and Irradiance Reflectance										
iz	zeta	z(m)	Eou	Eod	Eo	Eu	Ed	MUBARu	MUBARd	MUBAR	R = Eu/Ed
		in air	9.7675E-02	9.5298E-01	1.0507E+00	2.9105E-02	5.9866E-01	0.2980	0.6282	0.5421	4.8616E-02
1	0.00	0.00	2.3508E-02	6.7162E-01	6.9513E-01	9.4290E-03	5.7898E-01	0.4011	0.8621	0.8193	1.6286E-02
3	1.91	1.00	1.1631E-02	3.0982E-01	3.2145E-01	4.4336E-03	2.5288E-01	0.3812	0.8162	0.7729	1.7532E-02
5	3.82	2.00	5.1328E-03	1.3393E-01	1.3907E-01	1.9295E-03	1.0722E-01	0.3759	0.8006	0.7571	1.7995E-02
7	9.56	5.00	3.8325E-04	9.8290E-03	1.0212E-02	1.4244E-04	7.7349E-03	0.3716	0.7869	0.7435	1.8415E-02
9	19.11	10.00	4.6379E-06	1.1866E-04	1.2330E-04	1.7210E-06	9.3190E-05	0.3711	0.7853	0.7418	1.8467E-02

Table 1. Example of the default printout showing various irradiances, mean cosines, and the irradiance reflectance. The line labeled "in air" gives the values just above the air-water surface. Depth 0.00 is in the water, just below the surface. The user-requested output depths were z = 0, 1, 2, 5, 10 m. These are the odd-indexed depths (iz = 1, 3, 5, 7, 9); the even depths are used to compute K functions and are not shown in the default printout.

K-functions (units of 1/meter) (valid only when zupper and zlower are closely spaced)									
zupper	zlower	z	Kou(z)	Kod(z)	Ko(z)	Ku(z)	Kd(z)	Knet(z)	KLu(z)
0.000	0.010	0.005	0.53271	0.69107	0.68571	0.65229	0.79845	0.80088	0.77136
1.000	1.010	1.005	0.78821	0.81967	0.81853	0.80976	0.84798	0.84866	0.83940
2.000	2.010	2.005	0.83970	0.85297	0.85248	0.84853	0.86592	0.86623	0.86168
5.000	5.010	5.005	0.87829	0.88019	0.88012	0.87955	0.88207	0.88212	0.88124
10.000	10.010	10.005	0.88430	0.88422	0.88423	0.88424	0.88410	0.88409	0.88406

Table 2. The default printout showing the K functions corresponding to the irradiances of Table 3. The closely spaced pairs of depths (z_{upper} , z_{lower}) used to compute the K functions are now shown explicitly.

7.2 Examining Output with EXCEL

Selected output is written to two ASCII files that are intended for conversion to Microsoft EXCEL spreadsheets. This conversion is performed using EXCEL macros that are provided with HYDROLIGHT. These files contain roughly the same information as the default printout and, likewise, can be tailored to the individual user's desires. The two files, Mroot.txt and Sroot.txt (where "root" is the root name set in the Run Identification form of the UI), are written by HYDROLIGHT to the excel directory. They are structured as follows:

Mroot.txt will convert to an EXCEL workbook in which each sheet contains a single variable (such as the total absorption or the downwelling plane irradiance) as a function of depth and wavelength. This is the "multi-wavelength" format. This file is converted into a spreadsheet by running the macro multiwl.xls, which is in the excel directory.

Sroot.txt will convert to an EXCEL workbook in which each sheet contains several variables (such as the absorption, scattering, backscatter, and beam attenuation coefficients) as functions of depth, but grouped one wavelength at a time. This is the "single-wavelength" format. This file is converted into a spreadsheet by the singlewl.xls macro in the excel directory.

The way in which you run the macros depends slightly on the version of EXCEL you are using. The following example is for EXCEL 97 (EXCEL Version 7 follows the same procedure, but requires fewer steps because it does not give you the asinine warning messages). Suppose, for example, that you have made a multi-wavelength HYDROLIGHT run with the root name UGEx1. The excel directory should then contain files named MUGEx1.txt and SUGEx1.txt, as well as the macro files multiwl.xls and singlewl.xls (and any other Mroot.txt and Sroot.txt files from previous runs). To convert MUGEx1.txt to a workbook, follow these steps:

- start EXCEL
- select FILE ➜ OPEN
- go to the excel directory (under the HE5\OUTPUT directory), select multiwl.xls, click OPEN
- click ENABLE MACROS if you get a warning message about the dangers of running macros

- click OK if you get a message about having to use Visual Basic to open macros
- either hit CTRL-M or select TOOLS ➜ MACRO ➜ RUN (select the macro named Macro_multiwave if it is not automatically highlighted) to start the macro.
- click SELECT DATAFILE from the macro's startup screen.
- Browse to the Mroot.txt file you wish to convert and select it.
- The macro will run and convert the Mroot.txt file into a workbook.
- Click NO if you get a message asking if you want the information on the clipboard to be available later.
- The macro will ask if you want to save the workbook. If you answer YES, the default name for the workbook is MUGEx1.xls (Mroot.xls in general).

Whether or not you save the workbook, the macro leaves you in the EXCEL workbook that has been created. At this point you are simply using EXCEL without regard to how the workbook was created or to the fact that the data came from HYDROLIGHT. You can, for example, now block out data and use the EXCEL plotting functions to create simple plots of the HYDROLIGHT output. However, it is not the purpose of this users' guide to teach you EXCEL, so good luck and call the folks at Microsoft if you have questions about EXCEL.

Table 3 shows the first few rows of the first sheet of the workbook created in this example.

Run Title:	Users' Guide, Example Run					
abs coef	18	7				
a (1/m)						
wavelen	0	5	10	15	20	25
360	6.03E-02	6.89E-02	8.73E-02	1.15E-01	9.70E-02	5.56E-02
380	5.08E-02	5.91E-02	7.69E-02	1.03E-01	8.63E-02	4.62E-02
400	4.44E-02	5.31E-02	7.16E-02	9.91E-02	8.14E-02	3.96E-02
420	4.99E-02	6.07E-02	8.37E-02	1.18E-01	9.59E-02	4.39E-02
440	5.35E-02	6.47E-02	8.87E-02	1.24E-01	1.01E-01	4.73E-02
460	5.16E-02	6.15E-02	8.26E-02	1.14E-01	9.37E-02	4.62E-02
480	4.82E-02	5.65E-02	7.42E-02	1.01E-01	8.36E-02	4.36E-02
500	4.99E-02	5.67E-02	7.12E-02	9.27E-02	7.88E-02	4.62E-02

Table 3. An example of an EXCEL work sheet created from an Mroot.txt file. There is one variable (here, the absorption coefficient *a*) displayed as a function of wavelength (rows) and depth (columns).

Creating a workbook from the single-wavelength file proceeds in the manner just described, except that you run the macro named singlewl.xls and you give it the name of a file on the single-wavelength format, e.g., SUGEx1.txt in the present example. Table 4 shows the first few rows of the first sheet of the workbook created from the example single-wavelength spreadsheet file.

Run Title: Users' Guide, Example Run
Wavelength = 360.0 nm

depth (m)	a (1/m)	b (1/m)	c (1/m)	omega0	bb (1/m)
0	0.0603	0.3102	0.3705	0.8372	0.01146
5	0.0689	0.3794	0.4483	0.8463	0.01273
10	0.0873	0.5252	0.6125	0.8575	0.0154
15	0.1145	0.738	0.8525	0.8657	0.0193
20	0.097	0.6013	0.6983	0.8611	0.0168
25	0.0556	0.2717	0.3273	0.8302	0.01076

Wavelength = 380.0 nm

depth (m)	a (1/m)	b (1/m)	c (1/m)	omega0	bb (1/m)
0	0.0508	0.2919	0.3427	0.8519	0.00988
5	0.0591	0.3575	0.4166	0.8581	0.01108
10	0.0769	0.4956	0.5725	0.8656	0.01361
15	0.1034	0.6972	0.8006	0.8709	0.0173
20	0.0863	0.5677	0.6541	0.868	0.01493
25	0.0462	0.2554	0.3016	0.8469	0.00921

Table 4. The first few rows of the first worksheet created from an example Sroot.txt file. Note that there are several variables (columns) shown as functions of depth (rows), with a separate block of data for each wavelength.

The FORTRAN routines that write the Mroot.txt and Sroot.txt files are found on file maincode\excel.f. Subroutine WRTXCLS writes the Sroot.txt files and subroutine WRTXCLM writes the Mroot.txt files. Those routines contain extensive documentation explaining how to modify the routines to obtain more or less output for conversion to EXCEL spreadsheets.

7.3 Plotting Output with IDL

Many HYDROLIGHT users prefer the IDL software package for plotting output from HYDROLIGHT runs (IDL is Interactive Data Language, a product of Research Systems, Inc.). The examples\idl directory distributed with the HYDROLIGHT code contains the routines used to plot Figures 6-10 of this Users' Guide; the IDL files are named ugfig6.pro to ugfig10.pro. If you are familiar with IDL (and have the IDL software on your computer), running these routines will be straightforward. If you do not want to use IDL, you do not need the files on the examples\idl directory. These IDL routines are NOT a part of HYDROLIGHT, but are provided "as is" for the benefit of IDL users.

The IDL routine readall.pro (found on the idl directory) reads the HYDROLIGHT Droot.txt files. These large files contain *all* of the output from a HYDROLIGHT run and are formatted for ease of reading into IDL. All of the information contained in a Droot.txt file is made available to the IDL main program via common blocks. A main IDL program can then generate the desired plots using the appropriate HYDROLIGHT output. For example, to regenerate Fig 8 shown in the examples:

- start IDL, and change into the HE5\examples\idl directory by typing:
  cd, 'c:\HE5\examples\idl'
- to compile the code (this must be done each time you launch IDL) type:
  `.run ugfig7`
- to run the code type `mprrs, filename` (where `filename` is the text string name of the Droot.txt file you wish to process, including path, enclosed in single quotes, e.g., type:
  `.run mprrs,'..\example3\dugex3.txt')`
- choose normalization and printout options as prompted

Note 1. IDL will want to know the *filename* that contains the code it needs to compile, not the name of the function contained. For instance, the routine `mprrs` is contained in the file `ugfig7`, hence you compile `ugfig7` (not `mprrs`). Similarly, the file `ugfig8.pro` contains the function `asurf` which generates surface plots for the various IOPs.

Note 2. There is a point of perpetual confusion when using IDL to plot HYDROLIGHT output. In HYDROLIGHT, an N-dimensional array $A(i)$ is usually (but not always) indexed from 1 to N, i.e. $A(1)$ to $A(N)$. In IDL, array indices always begin with 0, so that the same array is indexed

as $A(0)$ to $A(N\text{-}1)$. This can be especially confusing when you are trying to extract blocks from multidimensional arrays in order to generate, for example, a polar-angle plot of the radiance in the azimuthal plane of the sun, at a given depth and wavelength (as in Fig. 8 above). To make matters worse, some HYDROLIGHT arrays are indexed beginning with 0. For example, the arrays that store irradiances use depth index 0 to store the irradiance in the air, just above the surface. In this case, the HYDROLIGHT and IDL array indices are the same. Most IDL users have learned to live with these sorts of indexing mismatches, but if you have not, be forewarned and do some extra debugging of your IDL routines to make sure you are plotting exactly the HYDROLIGHT output you want.

8. ADVICE ON RUNNING HYDROLIGHT

This section gives a few words of advice that may help you run HYDROLIGHT more efficiently.

8.1 Depth Considerations

The relevant measure of depth in radiative transfer theory is the dimensionless *optical depth* ζ, not the geometric depth z. This can lead to confusion in understanding HYDROLIGHT run times. For example, in homogeneous clear water at blue wavelengths, where the beam attenuation is $c \approx 0.02$ m^{-1}, 50 m is only about $\zeta = cz = (0.02 \text{ m}^{-1})(50 \text{ m}) \approx 1$ optical depth. In highly absorbing or scattering water with $c = 1$ m^{-1}, 50 m corresponds to 50 optical depths. In this case, HYDROLIGHT will require ~50 times as long to obtain a solution to the same geometric depth as it does in the clear water. This dependence of run time on optical depth causes an unavoidable run-time penalty when running HYDROLIGHT at red or near-IR wavelengths (out to 800 nm), where the absorption by pure water itself is as large as 2.5 m^{-1}. Runs to even a few meters of geometric depth require the solution of the RTE to many optical depths at long wavelengths, even in pure water. Thus, much of the total run time can be expended in solving the RTE at the longer wavelengths. Therefore, *do not run HYDROLIGHT to longer wavelengths than are really necessary to solve your problem*. If you do need output for wavelengths out to 800 nm, consider making two separate runs: the first covering wavelengths below 700 nm and going down to the needed geometric depth, and the second from 700 to 800 nm but stopping at a shallower geometric depth (since there will be little light below the first few meters of the water column). Then piece the two solutions together.

There is a very useful trick that can enormously speed up the HYDROLIGHT run time in one special situation. *If* (and only if) *you are modeling a homogeneous, infinitely deep water body (neglecting any fluorescence or internal sources) and the only output you need is the water-leaving radiance, then you can apply the bottom boundary condition at a nominal depth* (say, 0.1 m). (That is, request output only at depths 0.0 and 0.1 m and select the "infinitely deep water" bottom boundary condition.) The water-leaving radiances will be *exactly* the same as if you had solved the RTE to a greater depth, but the run time will be minimal. If you use this trick, you will of course not have any output for the light field below 0.1 m within the water, but that is irrelevant for remote-sensing studies. Note that the water-leaving radiances will not be the same in these "deep" and "shallow" simulations if the water IOPs vary with depth or if the water is actually shallow and the bottom boundary has significant effects on the emerging

light field. Also, the inelastic-scatter effects cannot be computed unless you run the simulation to sufficient depth.

HYDROLIGHT automatically solves the RTE with extremely fine depth resolution in the IOP's. The numerical algorithms can take very small depth steps (~10^{-6} optical depths or less) when solving the Riccati equations (*Light and Water*, Eqns. 8.74-8.85) that lie at the core of the HYDROLIGHT calculations. These calculations typically require about 90 percent of the run time. As already noted, the primary factor influencing the run time is the optical depth to which a calculation is performed. The run time is much less influenced by the depth dependence of the IOPs. Thus, for example, solving the RTE for the binned absorption profile seen in Fig. 1 (the left-hand curve) does not require much more time than solving the RTE for a homogeneous water body with the same average absorption profile. (This statement does have it limits, though, as discussed in Section 1.1.) This near independence of run time on IOP depth structure is one of the most powerful features of HYDROLIGHT.

HYDROLIGHT *saves* the computed radiances only at the *user-selected output depths* z_k, k = 1, 2, ..., K, which are specified along with the other input to a standard run. The output depths can be arbitrarily spaced in order to get detailed output in the regions of greatest interest, such as near the sea surface or near strong gradients in the IOP's, and less output in regions where there is little "fine structure." *It is very important to note that the solution of the RTE is entirely independent of where output is to be saved for later analysis.* For example, you might request output at one-meter depth intervals, i.e., $z_1 = 0$, $z_2 = 1.0$ m, $z_3 = 2.0$ m, ..., $z_6 = 5.0$ m, ..., and so on. On the other hand, you might request output at $z_1 = 0$, $z_2 = 5.0$ m, ..., and so on. The output at 5.0 will be exactly the same in both cases; the only difference is that we will have more output between 0 and 5.0 m in the first case. In particular, HYDROLIGHT does *not* solve the RTE with "one-meter depth resolution" in the first case and with "five-meter resolution" in the second case. The number of depths where output is saved does not significantly affect the run time (the only difference is the small amount of time required to write the output files). The size of the output files is, of course, directly proportional to the number of depths where output is saved.

The default array dimensioning supports output at 50 user-specified depths (strictly speaking, at 50 pairs of closely spaced depths, as described in Section 7.1). This parameter can be changed in the UI (via the PARAMETER LIMITS form) if output at more depths is needed.

Most oceanographers want output at *geometric* depths z_k, measured in meters, for ease of comparison with observational data. However, in some cases the output depths also can be specified as dimensionless *optical* depths ζ_k. This option is available only if the model is being run at just one wavelength, because the wavelength dependence of the IOP's makes a given

optical depth correspond to different geometric depths (different physical locations in the water column) at different wavelengths. Computations in terms of optical depths are convenient for general monochromatic radiative transfer studies, as opposed to specific oceanographic studies. Note that if the model is being run with optical depths, then the "ab" routine must be written to accept optical depth as input; of the example routines distributed with HYDROLIGHT, only abconst accepts both optical and geometric depths.

8.2 Wavelength Considerations

The various data sets built in to HYDROLIGHT give it the ability to run anywhere in the wavelength domain 300-1000 nm, which is of interest in optical oceanography.

There are two basic options for specifying the needed wavelength information. The first is to run HYDROLIGHT at a single wavelength. HYDROLIGHT then solves the *monochromatic* RTE with the IOP's, sky radiances, and bottom reflectance being taken equal to their values at the specified wavelength. Some routines, for example the "semi-analytical" sky model, have built-in data that are accurate to 1 nm resolution. Other routines, for example the absorption and scattering coefficients for pure water, may have data built in at 5 nm or 10 nm resolution. Such routines generally use spline interpolation to obtain IOP's at the requested wavelength. A run at a single wavelength can include an internal source term at that wavelength. Such a source term can represent a bioluminescing layer, for example. The output depths can be either geometric or optical depths. Monochromatic runs are most useful for general radiative transfer studies.

The second option is to run HYDROLIGHT over one or more contiguous wavelength bands with bandwidths $\Delta\lambda_j$, $j = 1, 2, ..., J$. When this option is chosen, the model automatically averages the input sky radiance over each wavelength band. This averaging smooths out the large nanometer-to-nanometer fluctuations in the sky radiance magnitude owing to Fraunhofer lines in the solar spectrum. However, *the absorption and scattering coefficients are taken to be the values at the band centers*. In principle, $a(z,\lambda)$ and $b(z,\lambda)$ also should be averaged over each band. However, this averaging would have to be performed every time the "*ab"* IOP subroutine is called with a new depth during the solution of the RTE; such averaging would be an enormous computational expense. If the band widths are of size $\Delta\lambda \le 20$ nm, then the replacement of band-averaged IOP values by band-center values will be acceptably accurate for most purposes, because IOP's (unlike the solar irradiance) do not fluctuate wildly on a nanometer scale.

Most present-day oceanographic and remote-sensing sensors have bandwidths of 5-20 nm. The bandwidths of a HYDROLIGHT run can be matched to these sensor bandwidths if desired. There is no requirement that the bandwidths $\Delta\lambda_j$ be equal for different j values. If the user wishes to simulate a wider-bandwidth instrument, then HYDROLIGHT should be run with a number of smaller bandwidths. The final output for the smaller bandwidths then can be averaged to get band-averaged output for the wide band. This approach properly accounts for the wavelength variation of the IOP's within the large band. Note that it is seldom necessary to make high-wavelength resolution runs. Figure 11 shows R_{rs} for a given set of IOPs and other input, but with output requested at resolutions of 1, 5, 10, 20, and 50 nm. Even with a resolution of 50 nm, the calculated R_{rs} *at the middle of the band* is nearly indistinguishable from the high resolution result. The reason is that HYDROLGHT uses the IOP values at the middle of the bandwidth in its calculations.

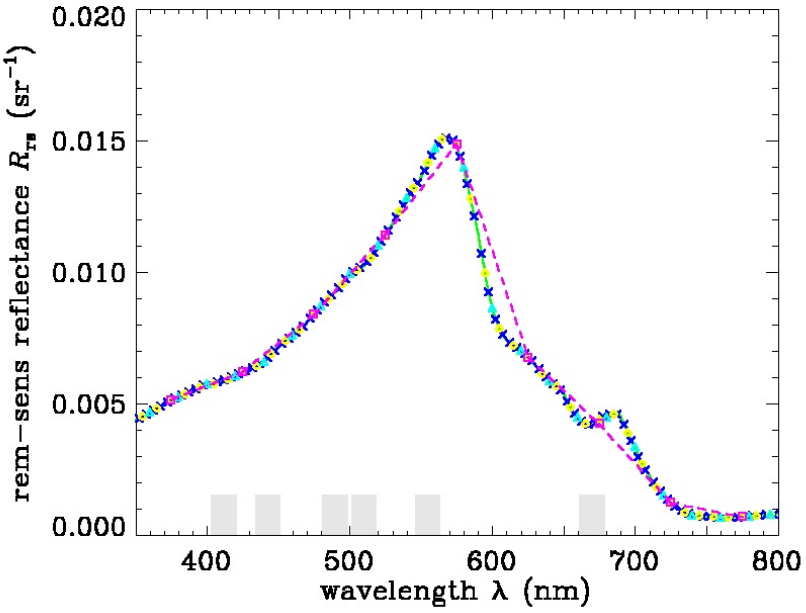


Figure 11. Remote sensing reflectance in a simulated Case 2 water body (5 mg/m^3 Chl, moderate CDOM, and 2 g/m^3 mineral) with output resolutions of 1 nm (solid green line), 5 nm (dark blue x), 10 nm (yellow circles), 20 nm (light blue triangles), and 50 nm (magenta squares connected by dashed line).

For calculations of PAR and fluorescence, HYDROLIGHT assumes the values across the bandwidth are constant and equal to the "mid band" value. You will need to select the resolution based on what you are trying to calculate. For instance, in Fig. 11, 50 nm resolution might be acceptable if all you want is a few specific R_{rs} values, however it is not sufficient to resolve the true shape of the R_{rs} curve as a function of wavelength.

Another consideration in the choice of wavelength bands arises in connection with inelastic scattering effects. Suppose, for example, that we wish to simulate the light field in the 450-500 nm region. If we are uninterested in inelastic-scattering effects from shorter wavelengths, then we could run HYDROLIGHT with five bands chosen as 450-460 nm, 460-470 nm, ..., 490-500 nm, for example. However, if we wish to include the contributions of fluorescence or Raman scattering to the light field in the 450-500 nm region, then HYDROLIGHT must be run for all wavelengths less that 450 nm for which there might be an inelastic-scattering contribution to the region of interest. Thus to include Raman scatter, the model should be run starting with a band from 390-400 nm, because wavelengths near 400 nm will Raman scatter into wavelengths near 450 nm. If CDOM fluorescence is to be included, then HYDROLIGHT should be run starting at 350 nm, because CDOM fluorescence can be excited by ultraviolet wavelengths and because CDOM fluoresces throughout the visible.

8.3 Inelastic Scattering and Bioluminescence

HYDROLIGHT has the option of running with or without inelastic scattering and internal sources being included in the RTE. The inelastic scattering processes included are chlorophyll fluorescence, CDOM fluorescence, and Raman scattering. The internal source usually is tailored to represent bioluminescence. If these effects are all omitted from the run, then HYDROLIGHT carries out a sequence of independent solutions of the monochromatic, source-free RTE. The solutions for different wavelength bands are then completely independent. However, if one or more of these effects are included, then the appropriate source terms are automatically added to the RTE, as described in *Light and Water*, Sections 5.14-5.16 and 8.7. In the case of inelastic scattering, the solutions in different wavelength bands are coupled by the inelastic scattering from shorter to longer wavelengths. The inelastic-scattering and internal-source computations in some cases call upon user supplied routines.

HYDROLIGHT models CDOM fluorescence using the spectral fluorescence quantum efficiency function of *Light and Water* Eq. (5.101), as shown in *Light and Water* Fig. 5.11. This particular function is built in to routine wrfcdom on file wrfdisc.f. The user can replace this default function with another, if desired.

Because Raman scattering depends only on the water itself, no user-supplied information is required. Various parameter values, such as the Raman cross section, are set to default values in routines setdflts and wrframen on file wrfdisc.f. Those values can be changed if desired.

Some additional computational expense results from the addition of the source terms seen in Eqs. (8.74)-(8.85) of *Light and Water*. However, the main increase in computation time when inelastic scattering is included arises from the need to run the model over wavelengths shorter than the wavelengths of interest, as was illustrated in the previous subsection. In the example discussed there, where the interest was only on 450-500 nm, including CDOM fluorescence effects on the 450-500 nm band requires about three times the computational expense, because the model then must be run from 350-500 nm.

HYDROLIGHT includes chlorophyll and CDOM fluorescence and bioluminescence exactly as formulated in Sections 5.15 and 5.16 of *Light and Water*. However, Raman scatter is included using an azimuthally averaged effective source term that is equivalent to the formulation seen in Appendix A of Mobley, et al. (1993). This simplification allows the Raman effective source term to be computed from the scalar irradiance (as is the case for fluorescence), rather than from the full radiance distribution. The azimuthally averaged formalism yields the correct Raman contribution to irradiances, which are computed from the azimuthally averaged radiance. However, the Raman contribution to the radiance is correct only as an azimuthally averaged value.

8.4 Setting Defaults

Many of the calculations performed within HYDROLIGHT assume default values for various parameters in order to minimize the input required from users for each run. These defaults can be simple numbers, such as the chlorophyll-fluorescence quantum efficiency; entire data sets, such as are used by the atmospheric models contained within the sky radiance models; or functions, such as the excitation-emission spectrum for CDOM fluorescence. In most cases, the default values are set to typical or average values for the marine environment; these default values may or may not be adequate for your particular simulation. Defaults are also used to set the amount and type of output obtained from a run.

There are a number of subroutines in the maincode directory where defaults are set. Some parameters of interest can be changed within the UI (for example, the maximum number of depths, type/amount of output, sky paramaters, etc.).

8.5 Making Special Runs

A special HYDROLIGHT run is required in three circumstances: (1) a new phase function is to be prepared and added to the collection of available phase functions, (2) a new surface wind speed is needed, or (3) a new quad layout is needed. Because of the infrequent need for making special runs, control of these runs is not incorporated into the front-end programs. Special runs can be made only by creating the needed input file with a text editor and then submitting the run from a command window; this is easy to do. Special runs are described in the Technical Documentation volume.

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APPENDIX A. LICENSE AGREEMENT FOR USE OF HYDROLIGHT AND ECOLIGHT 5

This license agreement is also contained in the source code and in the UI.

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