HYDROLIGHT TECHNICAL NOTE 9

OPTIONS FOR INPUT OF USER-DEFINED SKY IRRADIANCES

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These notes discuss several new options for input of user-defined sky irradiances into HydroLight-EcoLight version 5.1. The associated code upgrades HydroLight-EcoLight version 5 (HE5) to version 5.1.2. These notes serve as a User's Guide for the new code features, until new editions of the User's Guide and Technical Documentation are issued.

New Options for Input of Sun and Sky Irradiances

The new options allow users to input their own measured or modeled sun and sky irradiances in several ways, using data on Hydrolight Standard Format (HSF) data files. There are options to

1. **Input a file containing wavelength and total (sun + sky) irradiance**. HE5 will then call the built-in RADTRANX sky irradiance model to partition this total into direct (sun) and diffuse (sky) irradiances, as needed by the RTE solution code. File `Sky_Irrad_Example_Edtotal.txt`, which is placed in the `HE5\data\examples\` directory when the code is updated, shows the required HSF format for such files. When using this option, the sun angle and atmospheric conditions used by RADTRANX should match as closely as possible to the conditions for the user's irradiances, so that the partition into direct and diffuse parts will be as accurate as possible.

2. **Input a file containing wavelength, direct (sun), and diffuse (sky) irradiances.** File `Sky_Irrad_Example_Eddir_Eddif.txt` is an example. With this option, the sun zenith angle entered in the user interface (UI) is used to determine where the sun (whose direct beam is generates the user's direct irradiance values) should be placed, and the default Harrison and Coombs sky radiance model is used to determine the angular distribution of the radiance corresponding to the user's diffuse sky irradiances. However, RADTRANX will NOT be called, so the atmospheric information entered in the user interface (UI) will not be used.

3. **Input a file containing wavelength, total irradiance, and the fraction of the total that is direct irradiance.** File `Sky_Irrad_Example_Edtot_frac.txt` is an example. The direct irradiance will be computed from the total times the fraction, and the diffuse from the total times (1 minus the fraction). With this option, the sun zenith angle and sky radiance

models are used as for option 2, and RADTRANX will not be called.

4. **Input a lidar irradiance at a single wavelength and have the sky irradiance at all other wavelengths be set to zero.** This simulates a lidar input in an otherwise black sky. This option is a special case of option 2 above, and is discussed in detail below. File `Sky_Irrad_Example_Lidar488.txt` is an example. With this option, RADTRANX will NOT be called, so the atmospheric information entered in the user interface (UI) will not be used.

One limitation to running the standard HE5 outside the 300-1000 nm wavelength range is that the database underlying the RADTRANX sky irradiance model is defined only for those wavelengths. (The other limitation is that the IOP and bottom reflectance spectra are not defined for other wavelengths.) Because Option 2 does not call RADTRANX, **this option makes it possible to run HE5 over any wavelengths**. There are, however, important caveats to running HE outside of 300-1000 nm:

- Even though the user can input sun and sky irradiances for any wavelengths and run HE5, the IOPs and bottom reflectances will be given the values at the nearest wavelengths defined in their databases. For example, the concentration-specific absorption and scattering spectra found in `HE5\data\defaults` are defined only for 300-1000 nm, and even then the values near 300 and 1000 are often just educated guesses, because very few measurements of such things have been made outside ~350 to ~750 nm. **Thus the user should first update any needed IOP or bottom reflectance files to include values for the wavelengths of the desired run.**

- The default Harrison and Coombes model for the angular pattern of the sky radiance does not depend on wavelength, and thus becomes more and more inaccurate outside the visible wavelengths for which is was developed. This, however, should have little effect on computed AOPs.

- The index of refraction varies with wavelength, so the option to use a wavelength-dependent index should be chosen in the UI. This, however, should have almost no effect on computed AOPs.

In any case, if doing a run outside of 300-1000 nm, you must manually change the default wavelength limits in file `HE5\frontend\HFEdflts.txt` to allow the UI to run outside its standard 300-1000 nm range. This change is made to line 3 of that file, which in the standard code reads
300,1000,1
To enable HE to run from, say, 250 to 1500 nm, change this line to
250,1500,1
and save the file. It may also be necessary to increase the default maximum number of wavelengths on the UI "change limits" form.

Figure 1 shows the total, direct, and diffuse spectral plane irradiances incident onto the sea surface as computed by the MODTRAN version 4.0 (Acharya et al., 1998) atmospheric radiative transfer code and by RADTRANX for roughly the same input atmospheric conditions. MODTRAN was run from 350 to 1500 nm by 10 nm; RADTRANX can be run only to 1000 nm. One of the standard MODTRAN outputs is a file (`*.flx`) of computed irradiances at all levels in the atmosphere. The IDL program `Modtran_Ed_to_Hydrolight_Ed.pro`, which is placed in the `HE5\examples\idl` directory during the version 5.1.2 upgrade, reads MODTRAN `*.flx` files, extracts the sea-level irradiances, and saves them on a HSF format file. File `Sky_Irrad_Example_Eddir_Eddif.txt` was created in this way. MODTRAN and RADTRANX are much different in their inputs and calculations, so it is difficult to do corresponding simulations. Nevertheless, the figure shows that the total irradiances Ed_total computed by each are within ~10% of each other except in the strong atmospheric absorption bands. However, MODTRAN and RADTRANX partition the total into direct and diffuse components in much different ways.

Fortunately the differences in MODTRAN and RADTRANX irradiances make almost no difference in apparent optical properties (AOPs) such as the remote-sensing reflectance R_{rs}. That is, after all, why AOPs are of value. Figure 2 shows the R_{rs} spectra for these two sky inputs and for Case 1 water with a chlorophyll concentration of 5 mg m^{-3} (using the "new Case 1" IOP model in HE5). The R_{rs} spectra are the same to within 2% at all wavelengths, and they are usually much closer.

The code (in subroutine `HE5\code\common\irradat.f`) is set to read in the user's irradiances and assume that the data are values exactly at the listed wavelengths. The code then interpolates between the listed wavelengths to get sky irradiances at 1 nm resolution, and those values are then averaged over the run wavelength bands to get band-averaged irradiances (just as is done with RADTRANX values, which are at 1 nm resolution). This allows the run wavelengths to be independent of the data wavelengths. However, the values in the run printout for a given nominal wavelength will be slightly different than the values in the input data file for the same wavelength, because the printout shows the band-averaged irradiances, which depend on the size of the run wavelength bands as well as on the input data.

Because AOPs are almost unaffected by the incident sky irradiances, the main use of the new sky irradiance input options comes if radiometric variables themselves (radiances and irradiances) are to be compared with measurements or are required with great accuracy. Then it is critical to have accurate values of the input sun and sky irradiances, which set the magnitude of the entire computed light field. The other use of the new options is to allow HE5 to be run independently of RADTRANX, e.g., when it is necessary to make runs outside the standard 300-1000 nm range.

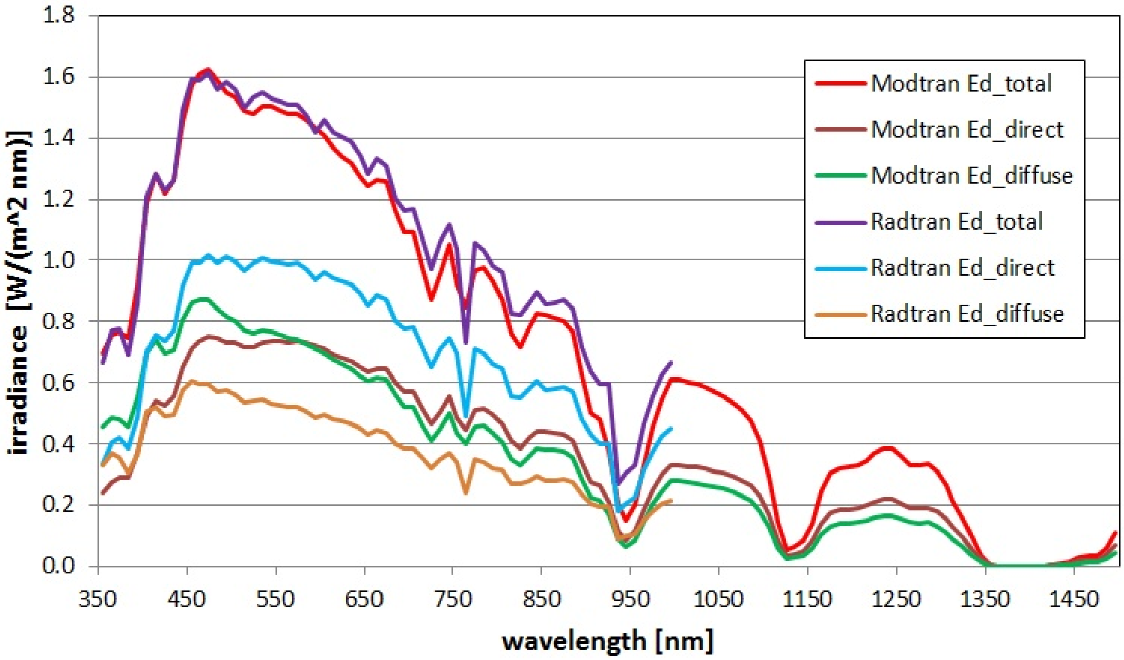

Fig. 1. Comparison of MODTRAN and RADTRANX sea-level radiances for roughly corresponding atmospheric conditions. Note that the total irradiances are close, but that the component direct and diffuse irradiances are much different for the two models.

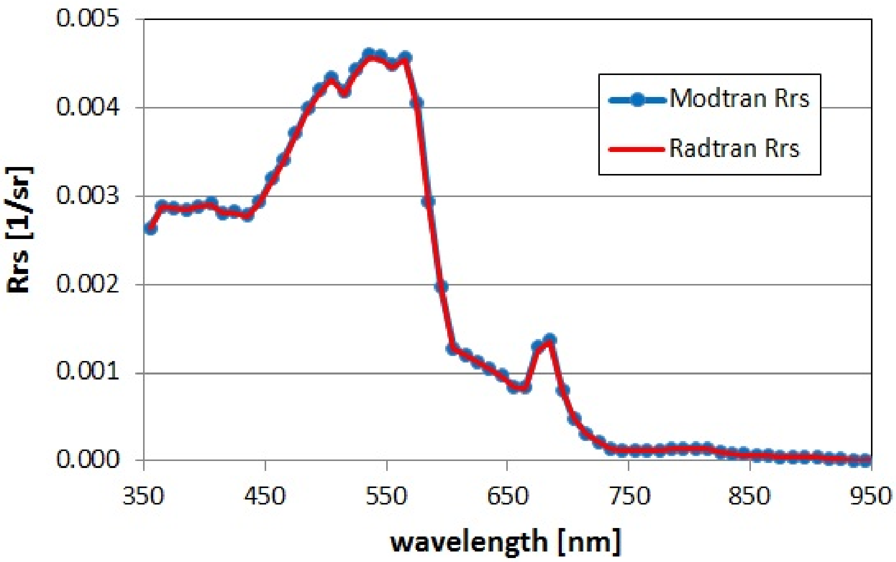

Fig. 2. Remote-sensing reflectances R_{rs} computed with the MODTRAN and RADTRANX input irradiances of Fig. 1, and Case 1 water with a chlorophyll concentration of 5 mg m^{-3}.

Simulation of Lidar-Induced Inelastic Scatter

It is also possible to use HE5 to simulate lidar-induced Raman scatter and CDOM and chlorophyll fluorescence. The code has been modified so that if the option 2 above for input of a file with Ed_direct and Ed_diffuse is selected, but there is only one wavelength in the file (not counting the negative wavelength that flags the end of data), then that input is taken to be a lidar input and all other bands in the run are given zero sky inputs, i.e., the sky is black except at the lidar wavelength.

To run a lidar simulation, do the following in the UI:

1. **Place the "sun" at the zenith** (zenith angle of 0) to simulate the lidar beam propagating straight down. (The other atmospheric parameters will not be used because RADTRANX will not be called, nor will the Harrison and Coombes sky model be called.)

2. Select the sky irradiance option for reading a user file containing direct and diffuse sky irradiance. **The file to be read must have the "one-wavelength" format seen in Fig. 3.** The lidar irradiance in W m^{-2} nm^{-1} should be entered as the Ed_direct value, with the Ed_diffuse value set to zero.

3. **On the wavelength form, it is necessary to enter a 1 nm wide band centered on the lidar wavelength, regardless of the wavelength resolution of the other bands.** You can enter all wavelength band boundaries manually, or use this trick: Enter the bands you want for the output using the "minimim, maximum, bandwidth" option, e.g. 480 to 720 by 5 nm. Hit "continue" to go to the next form. This will enter the wavelength band list onto the wavelengths form. Then back up to the wavelengths form and select the option to enter a list of wavelengths, and manually add a 1 nm wide lidar band at the appropriate location in the list of wavelengths. (Save the inputs when you get to the final form, so that the wavelength list will be saved for subsequent runs.) The final list of wavelengths for this example should then look like

   480, 485, 487.5, 488.5, 490, 495, ..., 715, 720

The red wavelengths were added manually to the list, to define the 1 nm lidar band centered at 488.0 nm. Note that the input irradiance in W m^{-2} nm^{-1} times the 1 nm bandwidth defines the lidar irradiance in W m^{-2}, as is conventional when describing lidar irradiance in a very narrow band.

This process was used in a series of EcoLight runs to simulate Raman scatter for an infinitely deep, homogeneous water body with a chlorophyll concentration of 0.5 mg m^{-3}, using the "new Case 1" IOP model. Bandwidths of 1, 5, 10, and 20 nm were used for the nominal run bandwidths, and the RTE was solved to a depth of 30 m; the wind speed was 0. Figure 4 shows the water-leaving radiance in the region of the Raman output band centered near 582 nm.

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Example direct and diffuse sky spectral irradiances for LIDAR SIMULATION in a black sky.
This example assumes the run is done for a 1 nm band from 487.5 to 488.5 containing input from a 488.0 nm Lidar,
plus other bands that can be anything (e.g., 5 or 10 nm bands).
For input files having ONLY ONE input wavelength (not counting the end of file record of negative values),
the sky is automatically made black (Ed_direct = Ed_diffuse = 0.0) at all bands other than the Lidar wavelength,
which is all direct Ed (the Lidar beam and nothing else).
For this example at 488 nm, the run bands defined in the User Interface MUST include a band from 487.5 go 488.5.
Also place the sun at the zenith (zenith angle 0.0) in the User Interface.
wavelength   Ed_direct    Ed_diffuse
    (nm)     (W/m^2 nm)    (W/m^2 nm)
   488.0         1.0          0.0
    -1.0        -1.0         -1.0
```

Fig. 3. Example HSF input file for lidar simulation at 488 nm. The first 8 header records are reduced in size for printing here.

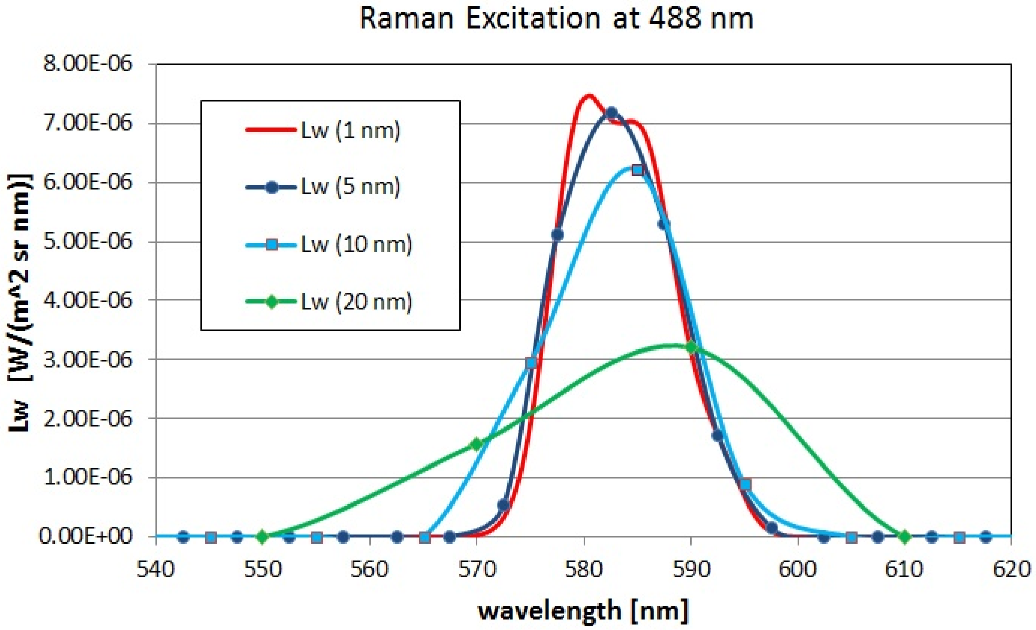

Fig. 4. Raman-generated, nadir-viewing, water-leaving radiance for excitation at 488 nm with 1 W m^{-2}. Only the output bandwidths differed in the EcoLight runs. Compare the qualitative shape of the red curve with Fig. 5.

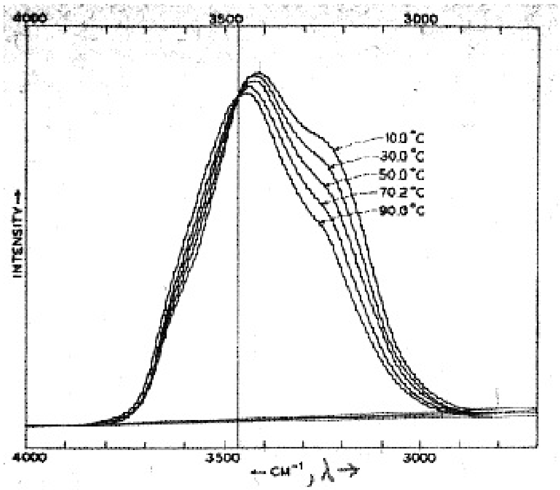

FIG. 6. Mercury-excited photoelectric Raman spectra of the intramolecular valence contours of water at temperatures from ~10°–90°C, obtained by Method A. The isosbestic frequency is emphasized by the vertical line at ~3460 cm^{-1}.

Fig. 5. Shape of Raman emission bands for water. The plot has wave number increasing to the left, corresponding to wavelength increasing to the right, as in Fig. 4. From Walrafen (1967).

Note in Fig. 4 that the run at 1 nm output resolution correctly reproduces the measured shape of the measured Raman water emission bands shown in Fig. 5. The curves are somewhat dissimilar because Fig. 4 is plotted as a function of wavelength, and Fig. 5 is in wave number (in cm^{-1}), so one set of curves is distorted relative to the other.

The fine structure of the Raman emission band is lost when the wavelength resolution is 5 nm or greater. Although the 5, 10, and 20 nm curves in Fig 4 look increasingly less like the true shape of the Raman emission band, the areas under the 1, 5 and 10 nm curves are the same to within 0.2%, indicating that the same total amount of energy is being Raman scattered in each case. The 20 nm resolution has the same total as for 1 nm resolution to within 5%.

Check on the Raman Scatter Calculations

It is easy to do a quick sanity check on the results of Fig. 4. The input lidar irradiance of $E_d(488) = 1\ \text{W m}^{-2}\ \text{nm}^{-1}$ over a 1 nm wide band gives a total input irradiance of $E_d(z{=}0,488) = 1\ \text{W m}^{-2}$ at the sea surface. This irradiance propagates to depth according to

$$E_d(z,488) \;=\; E_d(0,488)\,\exp[-K_d(488)\,z]\,, \tag{1}$$

if $K_d(z,488)$ is assumed to be independent of depth z. At each depth z, the amount of $E_d(z,488)$ that Raman scatters into *all* wavelengths is determined by the Raman scattering coefficient[1] $b^{\text{R}}(488) = 2.6\times10^{-4}\ \text{m}^{-1}$ according to

$$S^R(z,\Delta\lambda) \;=\; E_d(z,488)\,b^R(488)\,, \tag{2}$$

where $\Delta\lambda$ is the bandwidth receiving the scattered power, and S^{R} (with units of W m^{-3}) is a source term over the emission wavelengths. Raman scattering is roughly isotropic (to within 55%, see *Light and Water* Eq. 5.91), in which case the scattered power source term can be converted to an isotropic source term for scattered spectral radiance over the $\Delta\lambda$ band:

$$S_L^R(z,582) \;=\; \frac{S^R(z,582)}{4\pi\,\Delta\lambda}\,. \tag{3}$$

Here I have noted from Fig. 4 that light at 488 Raman scatters into a band $\Delta\lambda \approx 15$ nm wide centered near 582 nm. This source function can be used to compute the upwelling spectral radiance just below the sea surface, generated by Raman scattering at all depths:

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[1] In *Light and Water* page 294, this was referred to as the Raman absorption coefficient a_o^{R}, which was non-standard terminology.

$$L_u^R(0,582) = \int_0^\infty S_L^R(z,582)\, e^{-K_{Lu}(582)\,z}\, dz \tag{4}$$

$$= \frac{E_d(0,488)\, b^R(488)}{4\pi\, \Delta\lambda} \int_0^\infty e^{-K_d(488)z}\, e^{-K_{Lu}(582)z}\, dz$$

$$= \frac{E_d(0,488)\, b^R(488)}{4\pi\, \Delta\lambda\, [K_d(488) + K_{Lu}(582)]}\,. \tag{5}$$

In Eq. (4), $K_{Lu}(z,582)$ has been assumed independent of depth, and Eqs. (1)-(3) have been used in going from Eq. (4) to (5). Finally, the water-leaving radiance $L_w = L_u(z{=}0)/n^2$, where $n = 1.34$ is the index of refraction of water. The HydroLight runs that generated Fig. 4 also show that $K_d(z,488)$ varied from about 0.047 m^{-1} near the surface to 0.057 m^{-1} at 25 m depth. Likewise, $K_{Lu}(z,582)$ varied from about 0.044 m^{-1} near the surface to 0.055 m^{-1} at 25 m. Approximating each of these K functions by 0.05 m^{-1} and using the above values for the other factors in Eq. (5) gives a final estimate of

$$L_w(582) \approx \frac{E_d(0,488)\, b^R(488)}{4\pi\, n^2\, \Delta\lambda\, [K_d(488) + K_{Lu}(582)]}$$

$$\approx \frac{(1)\,(2.6\times10^{-4})}{4\pi\,(1.34)^2\,(15)\,(0.05+0.05)}$$

$$\approx 7.7\times10^{-6}\ \mathrm{W\,m^{-2}\,sr^{-1}\,nm^{-1}}\,.$$

Considering the crudeness of the approximations for the K functions and the angular distribution of the Raman-scattered light, this is a surprisingly good estimate of the numerically computed Raman-generated $L_w(582)$ near the center of the high-resolution (1 nm) simulation seen in Fig. 4.

Figure 6 shows one more example of lidar-induced inelastic scatter. EcoLight was run using the Case 2 IOP model, now with chlorophyll concentrations of first 1 and then 5 mg m^{-3}, extra CDOM with aCDOM(440) = 1 m^{-1} in each case, and no minerals. The run included Raman scatter, and chlorophyll and CDOM fluorescence. We now see the broad CDOM fluorescence output, the Raman peaks near 582, and the chlorophyll fluorescence peaks near 685 nm. The higher absorption in the chlorophyll = 5 mg m^{-3} case suppresses the amount of Raman and CDOM-fluoresced radiance leaving the ocean, but increases the size of the chlorophyll-fluorescence peak. These curves can be qualitatively compared with Fig. 5.9 of *Light and Water*.

It is important to keep in mind that HE5 lidar simulations still assume a horizontally homogeneous input irradiance (just as for sunlight). Thus you cannot simulate the propagation of a spot lidar with a beam diameter of a meter, for example, because that is an inherently three-dimensional radiative transfer problem.

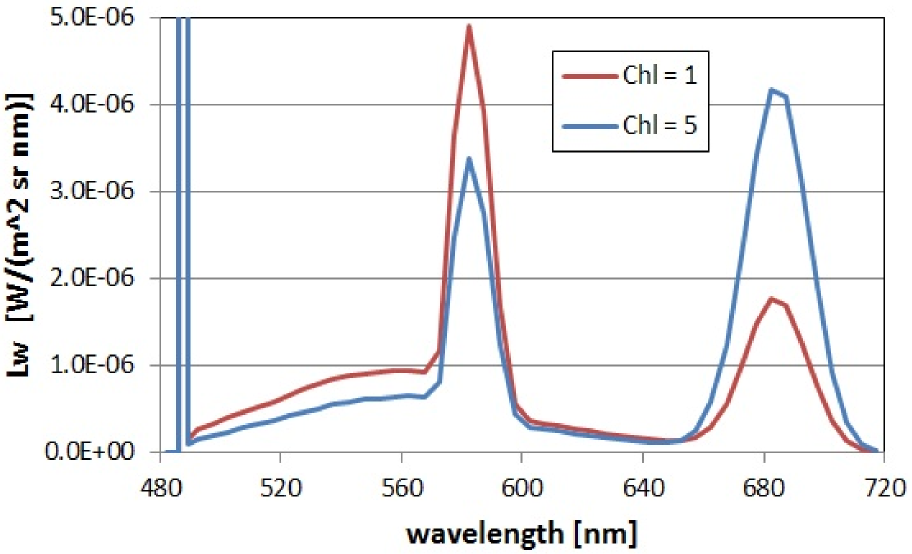

Fig.6. Examples of inelastic scatter induced by a 488 nm lidar for two chlorophyll concentrations and a high CDOM concentration.

As a final comment, suppose you want to simulate a lidar operating during daytime. The you effectively have two "suns" in the sky, the real one and the lidar beam. Allowing for that would require reprogramming the code that places the sun in the appropriate quad. However, you could do one run for the real sun and sky irradiances using option 2 or 3 above, and another for the lidar alone, and add the outputs for the two runs to get the combined sun, sky, and lidar signal.

References

Light and Water: Mobley, C.D., 1994. *Light and Water: Radiative Transfer in Natural Waters*. Academic Press. Available on CD from Curtis Mobley or at www.curtismobley.com/lightandwater.zip.

Acharya, P. K., et al., 1998. MODTRAN User's Manual Versions 3.7 and 4.0. Air Force Research Laboratory, Hanscom AFB, MA.

Walrafen, G. E., 1967. Raman spectral studies of the effects of temperature on water structure. *J. Chem. Phys.*, 47(1), 114-126.