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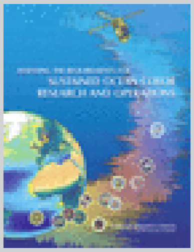

Assessing Requirements for Sustained Ocean Color Research and Operations

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Appendix C

Comprehensive Oceanic and Atmospheric Optical Datasets

Some past data collection campaigns have been designed only for validation of specific products without regard for subsequent possible uses and long-term value of the data. This results in a partial dataset, which, when later examined for other purposes, lacks one or more crucial "missing pieces" that preclude its use.

A comprehensive dataset has all the information necessary for a complete radiative transfer (RT) calculation to propagate sunlight from the top of the atmosphere (TOA), through the atmosphere to the sea surface, through the sea surface into the water, and then from the water back to the atmosphere, and finally through the atmosphere to the sensor. This RT process is the physical basis for all ocean color remote sensing and must be fully understood when evaluating the performance of any particular sensor and the products it generates.

Another way to summarize the necessary information is to keep in mind that to validate an environmental parameter or ocean color product (such as the chlorophyll or Colored Dissolved Organic Matter [CDOM] concentration, or depth and bottom type in shallow water), it first is necessary to validate the atmospheric correction algorithm, which requires knowing the absorbing and scattering properties of the atmosphere. To validate the bio-optical inversion algorithm that retrieves an ocean color product from the sea-level remote sensing reflectance, it is necessary to know both the value of the product and the water-leaving radiance. To understand how the product influences the water-leaving radiance, it is necessary to know the water absorbing and scattering properties (the inherent optical properties [IOPs]) and the in-water radiance distribution.

RT models are presently validated to the extent possible with incomplete datasets. In such exercises, the available IOP measurements plus reasonable assumptions about the missing pieces are used as inputs. The model predictions are then compared with the available radiometric measurements. However, there are always too many missing inputs and outputs to claim rigorous and complete model validation. Consequently, verification of a given model against independently developed numerical models becomes an expedient substitute for rigorous and complete model validation (e.g., Mobley et al., 1993).

The lack of comprehensive datasets is understandable given agency funding constraints for personnel, instrumentation, and ship time. Unfortunately, data collection for its own sake is almost never viewed as fundable science, even though model and algorithm development and validation always need comprehensive datasets. Finally, there are instrument limitations for measurement of some needed parameters. Nevertheless, the collection of even a few comprehensive datasets for selected water and atmospheric conditions would greatly advance ocean color remote sensing and environmental optics in general.

In addition to collecting the data needed for model and algorithm validation, data collection programs should be viewed as opportunities to compare various instruments and methodologies for making the same kind of measurement. Measurement redundancy is absolutely necessary in a field experiment.

The necessary measurements are dictated by the inputs needed to solve the radiative transfer equation (RTE) and to validate its output. Conceptually, atmospheric and oceanic absorbing and scattering properties + boundary conditions $\rightarrow$ RTE $\rightarrow$ radiance $\rightarrow$ other optical quantities of interest.

To validate a model or algorithm at one point and one time, simultaneous and co-located measurements are needed for the following quantities:

Oceanic Measurements

In principle, the two fundamental IOPs should be measured. See *Light and Water* (Mobley, 1994) or similar texts for a complete discussion of the quantities discussed here. These are the:

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- absorption coefficient $a(z,\lambda)$, measured as a function of depth z and wavelength λ.
- volume scattering function VSF(z,λ,ψ); ψ is the scattering angle, 0-180 degree.

What can be measured today:

Commercial instruments are available for in situ absorption measurements, and promising new instruments are under development.

No commercially produced instruments are currently available for in situ measurement of the VSF over the full range of scattering angles, but several unique instruments exist. Others are under development. Bench-top commercial instruments exist for measurements made on water samples. Given the current lack of readily available in situ VSF instruments, a reasonable proxy is to measure:

- the beam attenuation coefficient $c(z,\lambda)$, measured as a function of depth and wavelength.
- the backscatter coefficient $b_b(z,\lambda)$, measured as a function of depth and wavelength.

Commercial instruments are available for in situ measurement of beam attenuation, although (as with many measurements) there are instrument design issues that require standardization (Boss et al., 2009). The same is true for measurement of the backscatter coefficient.

Measurement of c allows the scattering coefficient b to be obtained from $b(z,\lambda) = c(z,\lambda) - a(z,\lambda)$. Knowing the scattering and backscatter coefficients allows the scattering phase function to be estimated from $b_b(z,\lambda)/b(z,\lambda)$, which can give acceptable inputs to the RTE (Mobley et al., 2002).

Boundary Conditions Needed to Solve the RTE

In principle the needed measurements are:

- the in-air, sea-level downwelling (sun and sky) radiance L_d(in air,θ,ϕ,λ) as a function of direction (polar angle q and azimuthal angle ϕ) and wavelength.
- the sea surface wave spectrum.
- the bidirectional reflectance distribution function, BRDF($\theta',\phi',\theta,\phi,\lambda$), of the bottom, if not infinitely deep water, as a function of all incident (θ',ϕ') and reflected (θ,ϕ) directions and wavelength.

What can be measured today:

Although these boundary conditions can be measured, they are almost never measured in the field because of instrument limitations. Therefore, it is reasonable to measure the following:

- the above-water, downwelling plane irradiance E_d(in air,λ) incident onto the sea surface, which can and should be partitioned into direct and diffuse contributions (Gordon, 1989).
- sun zenith angle (or compute from latitude, longitude, date, and time).
- sky and cloud conditions.
- wind speed.

Bottom irradiance reflectance R_b(l) = E_u(l)/E_d(l) can be used along with the assumption that the BRDF is Lambertian to obtain satisfactory predictions of water-leaving radiance for most remote sensing purposes (Mobley et al., 2003).

In-Water Outputs

Ideally, the following should be measured for comparison with RT model predictions:

- the full radiance underwater distribution $L(z,\theta,\phi,\lambda)$ as a function of depth, direction, and wavelength.
- the irradiances, $E_d(z,\lambda)$, $E_u(z,\lambda)$, and $E_o(z,\lambda)$, which give a consistency check by integrating the radiance to compare with the irradiances.
- the in-air upwelling radiance L_u(in air,θ,ϕ,λ).

What can be measured today:

There are no commercial instruments for in situ measurement of the full radiance distribution, although a few unique instruments do exist (Voss and Chapin, 2005). Commercial instruments are available for E_d and E_u, which are routinely measured. Commercial instruments are available for radiance measurements in a given direction, so radiance is usually measured only for selected directions (most commonly the upwelling direction, which can be used in estimating the remote sensing reflectance R_{rs}). An acceptable set of radiometric measurements is then:

- the upwelling (nadir-viewing), in-water radiance L_u(z,λ).
- the upwelling and downwelling in-water plane irradiances, E_d(z,λ) and $E_u(z,\lambda)$.
- the above-water upwelling radiance in one direction, e.g., L_u(in air,q=40,f=135,λ). The recommended direction is at 40 deg off-nadir and at 135-degree relative to the sun, which minimizes the sun glint (Mobley, 1999).
- the in-air downwelling (sky) radiance in the reflection direction, e.g., L_d(in air,q=40,f=135,λ), plus a gray-card measurement for estimation of E_d and R_{rs} (the so-called Carder method of estimating R_{rs}; see Mobley, 1999).
- the downwelling in-air plane irradiance, E_d(in air, λ) for both direct and diffuse lighting.

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Ancillary Measurements

These measurements are not needed to solve the RTE, but they are necessary for validation of bio-optical algorithms for retrieval of Chl, CDOM, TSM, etc. They also are needed to understand the fundamental connections between water column constituents and inherent optical properties. In principle, the following should be measured:

- Phytoplankton pigments (at the minimum, measure Chl-a).
- Absorption coefficient $a(z,\lambda)$ partitioned into the contributions by water, phytoplankton, CDOM, organic, and inorganic particles. At the minimum use filtered and unfiltered instruments to partition the absorption into dissolved and particulate contributions.
- The VSF(z,λ,ψ) (or total scattering and backscattering) partitioned into contributions by water, phytoplankton, and minerals (assuming CDOM is non-scattering). Chlorophyll-a is often the only pigment measured. Filtered and unfiltered instruments can be used to partition absorption into particulate and dissolved fractions. Partitioning the VSF into component concentrations is almost never done.

Atmospheric Measurements

To solve the RTE in the atmosphere, the same inputs are needed as for the ocean, viz. the atmospheric absorption and scattering properties and sea surface boundary conditions. However, these IOPs are usually cast in a different form, using a different vocabulary. The vastly greater path lengths needed for atmospheric attenuation measurements precludes the development of instruments that can directly measure the needed IOPs. The measurements that can and should be made are the following:

- Sea-level pressure, temperature, humidity, and wind speed. These are standard meteorological measurements that allow the Rayleigh scattering contribution to the atmospheric path radiance to be calculated.
- Atmospheric gas contributions to absorption are known for gases whose mixing ratios are constant. Ozone and water vapor concentrations are highly variable and need to be determined for detailed atmospheric RT calculations.

Aerosol concentration and optical properties are highly variable and remain the source of the greatest uncertainty in atmospheric RT calculations and atmospheric correction. The standard measurement used to deduce aerosol properties is sun photometry using, for example, the CIMEL sun photometer (the Aeronet, from which it is possible to extract the needed aerosol properties [Wang and Gordon, 1993; Dubovik and King, 2000]), which are:

- aerosol optical depth $\tau(\lambda)$ as a function of wavelength.
- aerosol scattering phase function.
- aerosol albedo of single scattering $\omega_o(\lambda)$ (= b/c, so related to the absorption and scattering coefficients).

If highly accurate atmospheric RT calculations are to be performed, vertical profiles of temperature, water vapor, and cloud type should be measured (typically with balloon-borne instruments or ground-based LIDAR). Ozone concentration should be determined from ancillary data such as sea-level measurements or satellite observation (e.g., the TOMS sensor) if RT calculations are to be done below 350 nm. Ozone can be optically important also in the visible part of the spectrum (the wide Chappuis band in the green wavelengths). In particular, the variations in the O_3 column content have to be accounted for when processing ocean color data, and the green signal (550-560 nm) corrected accordingly. It has also been demonstrated that nitrogen oxide may affect the blue channels.

Polarization

Polarization is an inherent feature of all electromagnetic radiation, including ocean color radiance. However, the ocean color community has usually ignored polarization with a few notable exceptions such as the POLDER satellite. This is both because of measurement difficulties and because unpolarized measurements can yield acceptably accurate answers for many (but not all) problems of interest. However, polarization carries information that can be exploited to improve ocean color product retrievals. For example, surface reflection is strongly dependent on polarization, so that sun glint is partially polarized, depending on the relative sun and viewing directions. In addition, biological and mineral particles have different indices of refraction and different size distributions, and thus scatter light differently, including polarization changes during the scattering. The French POLDER satellite exploited these effects to improve retrievals of biological vs. mineral particulate loads in the water.

Some atmospheric RT codes now include polarization (e.g., 6SV; Vermote et al., 2006), and a few researchers have developed proprietary coupled ocean-atmosphere RT codes. Polarization likely will become more important in future OCR applications. Therefore, the above measurements should be made with polarization in mind. Inclusion of polarization effects in RT computations requires the following measurements:

- Instead of the VSF (z,λ,ψ), measure the full Mueller matrix. The Mueller matrix has 16 elements, although not all are independent. The (1,1) element is the VSF.
- Instead of the radiance L, measure the Stokes Vector (4 elements).

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There are currently no instruments for in situ measurement of the Muller matrix, although one measurement of the full matrix has been made in the laboratory on a sea water sample (Voss and Fry, 1984). Instruments are under development for measurement of selected elements of the Muller matrix, which if available would enable underwater polarized RT calculations to be made for three elements of the Stokes Vector.

Unique instruments do exist for underwater measurement of the Stokes Vector (Tonizzo et al., 2009). Although such measurements are not yet common, they likely will become more so in the future.

Doing unpolarized radiative transfer in both the ocean and the atmosphere and using scalar (unpolarized) RT codes results in errors in the order of 10 percent in predictions of TOA radiances as needed for development and validation of satellite sensors and atmospheric corrections algorithms. The magnitude and wavelength dependence of the errors depend on the atmospheric and oceanic properties, sun angle, and viewing direction. The errors therefore cannot be quantified without detailed vector (polarized) RT calculations for the particular environmental and viewing conditions of interest. Therefore, the development of a user-friendly and publicly available coupled ocean-atmosphere vector RT code would greatly benefit future ocean color sensor and algorithm development.

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