

IN-WATER INSTRUMENTATION AND PLATFORMS FOR OCEAN COLOR REMOTE SENSING APPLICATIONS

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1 Introduction

Remote sensing of reflected sunlight from the upper ocean is a tremendous tool for studying biological, chemical, geological, and physical processes over a broad range of time and space scales. An orbiting satellite imager typically provides complete coverage of the global oceans in a day or two and is normally operational for periods of many years. Currently, there are several such remote sensors in operation, including the U.S. SeaViewing Wide Field of View Sensor (SeaWiFS), the Moderate Resolution Imaging Spectrometer (MODIS) sensors aboard the Terra and Aqua satellites, and the European Medium Resolution Imaging Spectrometer Instrument (MERIS). Global biogeochemical phenomena spanning seasonal (e.g., spring bloom), multi-year (e.g., the El Niño Southern Oscillation), to decadal (e.g., climatic variability) time scales can therefore be resolved.

Reflected light in the visible domain (wavelengths of ~400 to 700 nm) is particularly useful in the study of upper ocean processes, as many important biogeochemical components of seawater absorb and scatter light effectively in this spectral range (the term “ocean color” specifically relates to the spectral character of this water-leaving visible light). These dissolved and particulate seawater components play key roles in the dynamics and cycling of carbon in the ocean and serve as indicators of ecosystem health.

Down-looking, passive remote sensors in air and space measure sunlight that is reflected upward into the sensor; in addition to the atmospherically scattered photons, a portion of the measured radiance results from photons that have exited the ocean and passed back through the atmosphere to the sensor in orbit. This portion is termed water-leaving radiance, L_w ($\text{W m}^{-2} \text{nm}^{-1} \text{sr}^{-1}$) and primarily consists of light scattered in the backward direction off the particles and molecules of seawater. Sunlight incident at the ocean surface is represented as surface irradiance, E_s ($\text{W m}^{-2} \text{nm}^{-1}$), and the so-called remote sensing reflectance, R_{rs} , is derived from L_w/E_s , with L_w strictly defined in the nadir direction (normal to the plane of the ocean surface). Although L_w consists of primarily backscattered light, equally important in terms of its information content is the component of incident sunlight missing in the upwelled light. This is light that has been absorbed (or filtered) by the constituents of seawater in the upper ocean. The dependence of R_{rs} on these optical processes of backscattering and absorption can be simply written (Morel and Prieur 1977):

$$R_{rs} = \frac{L_w}{E_s} \cong f\left(\frac{b_b}{a + b_b}\right), \quad (1)$$

where the factor f varies within a relatively small range depending on surface illumination conditions and the volume scattering properties of the water body (Morel and Gentili 1996).

Understanding how the different components of seawater alter the path of sunlight through backscattering and absorption is essential to using remotely sensed ocean color observations effectively. This is particularly true in coastal waters where the different optically significant components (phytoplankton, detrital material, inorganic minerals, etc.) vary widely in concentration, often independently from one another. This understanding is packaged in the form of algorithms that define the relationships between biogeochemical components of seawater and remotely sensed signals. These algorithms are commonly known as inversions because the forward problem of incident sunlight being altered by the constituents in the upper ocean to produce a reflected signal is typically inverted in an algorithm to derive in-water constituent(s).

A multitude of algorithms or models have been developed to derive oceanic biogeochemical properties and these continually evolve as technological and theoretical advances clarify optical-biogeochemical relationships. Remote sensing algorithms typically fall into three categories: analytical, semi-analytical, and empirical. Analytical algorithms are based solely on theory; there are, however, very few purely analytical algorithms because they require detailed knowledge of a host of complex and often poorly understood relationships between seawater components and their specific optical properties (Morel 1980; Morel and Maritorena 2001). The more popular semi-analytical algorithms are based on theoretical relationships of the underlying physics of ocean color (such as **Eq. 1**) but include some statistical relationships formulated through data sets of relevant in-water parameters and optical properties. Empirical algorithms are based purely on these statistical regressions and are currently the most common type for oceanic case 1 waters. For important biogeochemical parameters (e.g., chlorophyll), several algorithms of each type have been developed.

In-water optical data are required for development, refinement, and validation of these algorithms. As a result, NASA, the U.S. Office of Naval Research, and foreign counterpart agencies maintain large repositories of in-water optical and biogeochemical data for current and future algorithm related needs (e.g., the SeaWiFS Bio-optical Archive and Storage System – SeaBASS, <http://seabass.gsfc.nasa.gov/>; World-wide Ocean Optics Database – WOOD, Smart 2000). For all algorithms, measurements of R_{rs} and the biogeochemical property in question are necessary for validation (note that R_{rs} computed based on below water measurements, and that measured above the water surface have been shown to agree within about 5% when appropriate care is taken with the measurement procedures – Hooker et al. 2002, Hooker and Morel, 2003). Also, regardless of the algorithm, measurements of R_{rs} are always necessary to validate and calibrate the signal detected by a remote sensor. These data sets are normally (hopefully) comprehensive, collected in many locations throughout the world’s oceans under conditions that cover a large dynamic range in the biogeochemical property. Using such data sets, statistical empirical algorithms have been developed to determine chlorophyll (e.g., O’Reilly et al. 2000), particulate organic carbon (Stramski et al. 1999;

Mishonov et al. 2003), calcium carbonate (Gordon and Balch 2003), macrophyte leaf-area index (Dierssen et al. 2003), oil (De Domenico et al. 1994), nutrients (Goes et al. 2003), and total suspended matter (Kratzer et al. 2000; Berastegui et al. 2003; Clark 2003).

Semi-analytical algorithms typically use an analytical model (e.g., Morel 1980; Morel and Gentili 1996; Zaneveld 1995) to derive the in-water optical properties of backscattering and absorption from R_{rs} but also require the use of empirical relationships between these optical properties and seawater constituents. As a result, development and validation work require measurements of R_{rs} , the biogeochemical property in question and the in-water optical properties used in the model. Semi-analytical algorithms are typically required in optically complex case 2 (coastal) waters. Semi-analytical models have been developed to derive chlorophyll (Gordon et al. 1988; Morel 1988; Roesler and Perry 1995; Carder et al. 1999; Ciotti et al. 1999; Maritorena et al. 2002; and many others), colored dissolved organic matter (Carder et al. 1999; Siegel et al. 2002), particle size distribution (Roesler and Boss 2003), and total suspended matter (Haltrin and Arnone 2003). Other algorithms such as those for total primary productivity (Platt and Lewis, 1987; Sathyendranath et al. 1989; Morel 1991; Antoine and Morel 1996; Antoine et al. 1996; Behrenfeld and Falkowski 1997; Campbell et al. 2002) and new production (e.g. Lewis et al. 1988; Dugdale et al. 1989; Sathyendranath et al. 1991; Siegel et al. 2002) use multiple derived products. So-called Algorithm Theoretical Basis Documents (ATBDs) for the MODIS sensors can be viewed at <http://modis-ocean.gsfc.nasa.gov/qa/dataproductmap.html>.

Some algorithms focus on retrieving the in-water optical properties from the remote signal (Garver and Siegel 1997; Gould and Arnone 1998; Hoge and Lyon 1999; Loisel and Stramski 2000; Loisel et al. 2001; Roesler and Boss 2003). The in-water optical properties themselves can be useful for radiative transfer modelling, biogeochemical classifications, or other applications such as estimating diver visibility (Zaneveld and Pegau 2003).

In addition to passive remote sensors on satellites and aircraft, active remote sensing techniques such as lidar actively stimulate the upper ocean with a laser source. When the wavelength of the laser light is appropriately chosen, this technique can be effective in sensing fluorescent compounds such as dissolved organic matter and phytoplankton pigments (Hoge et al. 1995; Hoge et al. 1998). Additionally, because the signal can be range-gated, depth profiles of absorption and backscattering can be obtained. As a result, parameters such as mixed layer depth may be derived, as long as waters above and below the thermocline have different backscattering and absorption properties, which is commonly the case (R. Zaneveld, personal communication, 2002).

In the following sections, in-water measurements and sensors that complement the requirements of remote sensing applications are discussed in more detail. Because the temporal and spatial characteristics of remote sensing relative to the data used for biogeochemical algorithm development and validation is of critical importance, the various types of deployment platforms that can be used to collect the in-water measurements are also discussed. Finally, brief comments are offered on strategies for collecting data for various remote sensing applications from a technology perspective.

This work is intended as a review of technology and techniques but we also hope that the context of the information will help to enhance strategies for using in-water instrumentation and platforms for algorithm development and validation in the future.

Reviewing current technology as well as current needs should also provide some insight toward pathways for future technology development.

2 In-water Instrumentation

In-water optical properties are classically broken down into two main types, “Inherent” and “Apparent,” after Preisendorfer (1976). Both are relevant to remote sensing applications. Inherent Optical Properties (IOPs) are those parameters whose magnitude depend only on the substances in the water and are independent of the ambient light field. Apparent Optical Properties (AOPs) are additionally dependent on the ambient light field and its geometrical structure. Radiative transfer theory describes the relationship between the AOPs and IOPs (e.g., Mobley 1994). The following provides general backgrounds and summarizes sensor technologies for each type. Specific issues relating to the deployment of optical sensors in the field (e.g., biofouling) are addressed in **section 3**.

2.1 INHERENT OPTICAL PROPERTIES

2.1.1 IOP background

Two fundamental IOPs are a (m^{-1}) and b (m^{-1}), the rates of radiant intensity loss over a fixed pathlength due to the processes of absorption and scattering, respectively. The beam attenuation coefficient, c (m^{-1}), is defined by their sum:

$$c \equiv a + b. \quad (2)$$

There are many ways to decompose total or integrated IOPs into constituent IOPs. Scattering, for example, can be partitioned with respect to its angular distribution:

$$b_x = 2\pi \int_i^j \sin(\theta) \beta(\theta) d\theta \quad (\text{where subscript } x = b \text{ or } f), \quad (3)$$

where $\beta(\theta)$ is the volume scattering function (VSF). The parameters b_b and b_f are the backward and forward components of b obtained by integration of **Eq. 3** over $[i = \pi/2, j = \pi]$ and $[i = 0, j = \pi/2]$, respectively, so that

$$b = b_b + b_f. \quad (4)$$

For the various semi-analytical and analytical remote sensing algorithms based **Eq. 1**, we now have defined the two key IOPs relevant to the remote sensing reflectance, a and b . These IOPs are then often separated into operationally defined components such as the dissolved and particulate fractions and water:

$$a_t = a_g + a_p + a_w, \quad \text{and} \quad (5)$$

$$b_{bt} = b_{bp} + b_{bw}, \quad (6)$$

which applies to **Eq. 2** as:

$$c_x = a_x + b_x \quad (\text{where subscript } x = t, g, p, \text{ or } w). \quad (7)$$

The subscripts t , g , p , and w represent total, dissolved (historically called gelbstoff or gilvin), particulate, and water, respectively. Operationally, the dissolved fraction typically comprises all substances that pass through a 0.2 μm filter. Other commonly used parameters are a_{pg} and c_{pg} , defined as the quantities $(a_p + a_g)$ and $(c_p + c_g)$, respectively.

Eq. 6 assumes that scattering from dissolved molecules in seawater will be negligible compared to the other terms. Another common assumption with errors typically less than 1% (Twardowski and Donaghay 2001) is that $c_g \approx a_g$ because the total scattering from dissolved materials in natural waters, b_g , is sufficiently low relative to a_g . This may be disputed, however, in waters with a high content of fine clays, where colloidal material passing through a 0.2 μm filter may be detectable (Aas 2000).

For algorithms focusing on the absorption and backscattering by phytoplankton, an additional partitioning of the particulate component of **Eqs. 5** and **6** is often made:

$$a_p = a_\phi + a_d, \text{ and} \quad (8)$$

$$b_{bp} = b_{b\phi} + b_{bd}, \quad (9)$$

where the ϕ and d subscripts represent the algal and non-algal components, respectively. The non-algal component is comprised of non-living particulate organic material, living particles such as bacteria, inorganic minerals, and bubbles. The relative contributions of these different particle groups to particulate backscattering is poorly known, but recent progress has been made (Stramski et al. submitted). All the IOPs in **Eqs. 2-9** have wavelength dependencies, examples of which can be found throughout the books by Shifrin (1988), Kirk (1994) and Mobley (1994).

Fluorescence is also an IOP that can be detected with passive and active remote sensing techniques. Common fluorophores in the dissolved fraction include humic substances (humic and fulvic acids), proteins, and hydrocarbons. Fluorescent phytoplankton pigments include chlorophyll, phycoerythrin, and phycocyanin.

The IOP fractional components discussed in this section can be related to several biogeochemical parameters (**Table 1**). Algorithms exist to derive nearly all of these IOPs from passive remote sensing or active lidar platforms (Garver and Siegel 1997; Hoge and Lyon 1999; Roesler and Boss 2003) and, as a consequence, remote sensing algorithms have been developed for many of these biogeochemical properties. Excellent IOP reviews, including components and some biogeochemical associations, are given in Shifrin (1988), Kirk (1994), and Mobley (1994).

2.1.2 In-water measurement of IOPs

Recent advances in in-water optical instrumentation and methodologies now enable the derivation of the IOP components included in **Eqs. 5-7** (Moore 1994; Pegau et al. 1995; Pegau et al. 1999; Twardowski et al. 1999; Moore et al. 2000; Mueller et al. 2003). The IOPs of pure water (a_w , c_w , b_w , and b_{bw}) can be considered knowns in the visi

Table 1. Some biogeochemical properties derived from optical properties.

Biogeochemical property	Optical Property	Example Reference(s)
Particulate Organic Carbon (POC)	1) c_p or b_p	Peterson 1978; Gardner et al. 1993, 2001; Loisel and Morel 1998; Bishop 1999; Bishop et al. 2002; Claustre et al. 1999, 2000; Mishonov et al. 2003
	2) b_{bp}	Stramski et al. 1999; Balch et al. 1999
Total Suspended Matter (TSM)	1) c_p or b_p	Peterson 1978; Gardner et al. 1993, 2001; Walsh et al. 1995; Prahel et al. 1997
	2) turbidity	Fugate and Friedrichs 2002
Dissolved Organic Matter or Carbon (DOM, DOC)	1) a_g	Pages and Gadel 1990; Vodacek et al. 1997
	2) Fluorescence	Coble et al. 1993; Ferrari et al. 1996; Klinkhammer et al. 2000
DOM composition ^a	1) a_g , spectral shape	Carder et al. 1989; Blough and Green 1995
	2) Fluorescence, multi-spectral shapes	Coble 1996; Del Castillo et al., 1999; McKnight et al. 2001
Chlorophyll	1) a_p	Bricaud et al. 1998; Claustre et al. 2000
	2) Fluorescence	e.g., Yentsch and Menzel 1963; Claustre et al. 1999
Phycobiliproteins	Fluorescence	Cowles et al. 1993; Sosik et al. 2002
Phytoplankton pigment ratios	a_p , spectral shape	Trees et al. 2000; Eisner et al. 2003
Proteins	Fluorescence	Coble et al. 1993; Mayer et al. 1999
Hydrocarbons	Fluorescence	e.g., Holdway et al. 2000
Particle size distribution	1) c_p , spectral shape	Morel 1973; Boss et al. 2001
	2) $\beta(\theta)$	Brown and Gordon 1974; Zaneveld et al. 1974; Agrawal and Pottsmith 2000
Particulate refractive index	1) $\beta(\theta)$	Brown and Gordon 1974; Zaneveld et al. 1974
	2) $c_p(\lambda)$, b_{bp} , and b_p	Twardowski et al. 2001
Sewage	Fluorescence	Petrenko et al. 1997
Nitrate	UV absorption	Johnson and Coletti 2002

^aFor example – ratio of dissolved humic acid to fulvic acid, DOM molecular size distribution, DOM aromaticity, DOM source

ble range with small error (Morel 1974; Pope and Fry 1997). Since no current in-situ method can physically separate phytoplankton pigments from an absorption measurement, the component IOPs in **Eqs. 8** and **9** must be derived from in-situ a_p and b_{bp} using bio-optical decomposition models (e.g., Roesler et al. 1989; Bricaud and Stramski 1990; Carder et al. 1999).

One of the most significant advancements for the measurement of IOPs has been the development of multi-wavelength combination a and c meters (Moore et al. 1992; Zaneveld et al. 1992). With precision optoelectronics and a relatively long 25 cm pathlength, these sensors are capable of resolving natural oceanic and coastal levels of a and c . The absorption measurement is based on the reflective tube principle (Zaneveld and Bartz 1990; Kirk 1992). Both the directly transmitted light from a collimated incandescent source and most of the forward scattered light within the reflective flow tube are collected using a diffuser and wide-area photodiode detector at the end of the tube. Since most of the scattering in the ocean is near-forward, only a small amount of light is lost in the flow tube (on the order of 10%) and corrections exist to account for this (Zaneveld et al. 1994). The c measurement uses a conventional collimated source and detector configuration (Bartz et al. 1978). The a and c measurements are blanked to clean water, and thus the parameters a_{pg} and c_{pg} are directly measured. Spectral a_g may also be measured by attaching a particle filter to the intake of the absorption tube (Twardowski et al. 1999, 2004). Detailed protocols for using these measurements to obtain the non-water parameters in **Eqs. 5** and **7** are described in Mueller et al. (2003).

A next-generation, hyperspectral a and c device has also been recently developed (Moore et al. 2004; Sullivan et al. 2004). The measurement principles are similar to previous a and c devices, but the spectral resolution is about 4 nm in the visible range. With the almost 10-fold increase in spectral resolution over previous sensors, spectral alignment of in-situ IOP data with current and future remote imagers should be readily accomplished. Sullivan et al. (2004) have been able to document naturally occurring hyperspectral structure in a and c with this device occurring over small scales not resolved previously.

Another device for measuring hyperspectral absorption that employs a long-pathlength liquid-waveguide capillary cell (Kirkpatrick et al. 2000) was recently adapted from the bench top to an in-water form installed in an autonomous glider vehicle (Schofield et al. 2004). The sensor is designed to determine distributions of the harmful algae *Karenia brevis* through a 4th derivative spectral analysis. Such in-water data combined with remote sensing may prove a powerful tool in assessing the dynamics of harmful algal blooms and may provide the groundwork for the development of remote sensing algorithms based on the *K. brevis* detection model (e.g., Schofield et al. 1999).

For measurements of backscattering coefficients, determinations of the VSF are made in the backward direction (**Fig. 1A**). Backscattering coefficients can then be derived using measured volume scattering coefficients at one (Maffione and Dana 1997; Boss and Pegau 2001) or more (Petzold 1972; Moore et al. 2000; Zhang et al. 2002; Lee and Lewis 2003) angles with errors of a few percent. Such small errors result from the observation that the shape of the VSF in the backward direction varies by small amounts, especially in the region of 90°-150°, which dominates the integrated backscattering coefficient because of the $2\pi\sin(\theta)$ term (Boss and Pegau 2001; see **Eq. 3**). Every measurement of the VSF in reality resolves a weighted portion of the VSF, where the weighting function, $W(\theta)$, describes the probability distribution for a scattering measurement based on the geometry of the sensor (e.g., source half-angle and detector field-of-view properties). The reported β angle of a VSF sensor is typically the centroid angle of the $W(\theta)$. For example, the weighting functions for a VSF sensor measuring scattering at 100°, 125°, and 150° are provided in **Fig 1B**. Raw backscattering counts may be calibrated to volume scattering coefficients using

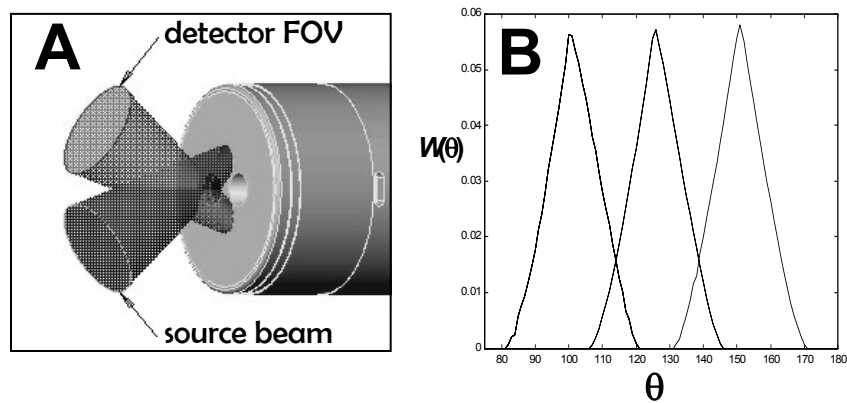


Figure 1. (A) A schematic of a volume scattering measurement with a backscattering sensor and (B) the weighting functions, $W(\theta)$, for a 3 angle (100°, 125°, and 150°) backscattering sensor.

theoretically defined weighting functions and solutions of particles such as microspherical beads that have known scattering properties (Moore et al. 2000) or by employing a Lambertian-reflecting plaque (Maffione and Dana 1997). In extensive field studies, sensors calibrated with the different methods have been shown to agree within ~10% (Boss et al. 2004).

For in-situ measurements of fluorescence, raw fluorescence counts are typically calibrated to a standard such as quinine sulfate, coproporphyrin, or vicariously calibrated to a rigorous bench top spectrofluorometer (Conmy et al. 2004). In the instance that the Raman scattering peak can be resolved in emission spectra, then calibration can be carried out by normalizing emission spectra to the integrated area under the Raman peak (Determann et al. 1998). The Raman-based calibration is the most accurate as long as the emission spectrum is already quantum corrected because the result is independent of excitation and emission spectral bandwidths, spectral resolution, and integration times. This technique also accounts for “inner filter effects,” or the attenuation of the excitation and emission beams experienced along the optical path within the sample. Devices with hyperspectral fluorescence emission that are planned for in-situ operation are currently in development with promising preliminary results (C. Moore, personal communication, 2004).

A wide variety of single and multiple channel in-situ fluorometers have been developed for measuring fluorophores such as chlorophyll, phycoerythrin, phycocyanin, and fluorescent DOM (e.g., Desiderio et al. 1993; Moore 1994). Many single channel sensors now use light-emitting-diode (LED) sources, as the intensity and spectral coverage of commercially available LEDs continue to improve. Notable multi-channel fluorometers include a 6-wavelength excitation, 16-wavelength emission device employing a xenon flash-lamp to effectively excite fluorescence in the ultraviolet (UV) (Desiderio et al. 1996; Del Castillo et al. 2000; Conmy et al. 2004), and a UV laser-induced fluorescence (LIF) system with 13-wavelength emission (Sivaprakasam et al. 2003). Flow cytometry technology measuring the fluorescence properties of individual cells has also been recently made submersible with promising results (Sosik et al. 2002).

A recent focus in new sensor development has been IOP (and AOP) sensors compatible with compact, autonomous deployment platforms (see **section 3**). Such

platforms require small sensors that are preferably hydrodynamic with very modest power requirements. For sensors that already have those attributes (e.g., many backscattering devices and single-channel fluorometers), adaptation for deployment on an autonomous platform may not require significant modifications (e.g., Yu et al. 2002). Mechanical installation and data handling are the primary challenges. For sensors that do not have those attributes (e.g., a and c meters and multi-channel fluorometers), new methods and sensors must be developed.

This gap in technology has recently led to the development of a new methodology and sensor for measuring c that is compatible with compact autonomous platforms (Twardowski et al. 2002, 2003). The technique uses two measurements of backscattering made at the same angle but over different pathlengths (**Fig. 2**). This allows for the rigorous measurement of c over relatively long pathlengths (more than 20 cm) with a hydrodynamic sensor only several cm's in length. A simple relationship between c and the scattering measurements S_1 and S_2 is theoretically expected and observed:

$$c \propto \ln\left(\frac{S_1}{S_2}\right). \quad (10)$$

The proportionality can be determined through vicarious calibration with conventional beam attenuation meters. Because the measurement is ratiometric, the device is self-calibrating with respect to fluctuations in source intensity. Developments such as this can extend the capabilities of optical sensors to autonomous platforms capable of sampling time-space scales relevant to remote sensing applications.

2.2 APPARENT OPTICAL PROPERTIES

2.2.1 AOP background

The fundamental apparent optical property is the radiance distribution ($L(\theta, \Phi, \lambda)$, units of $\text{W m}^{-2} \text{nm}^{-1} \text{sr}^{-1}$ or quanta $\text{m}^{-2} \text{s}^{-1} \text{nm}^{-1} \text{sr}^{-1}$), described as the radiant power in a specified zenith (θ) and azimuth (Φ) direction per unit solid angle, per unit area normal to the incident beam per unit wavelength. It is an apparent property in that the radiance distribution in the sea (and above it) results from the modification of the incident radiance field by the sea-surface, the inherent optical properties of the ocean interior, and the reflectivity of the sea bottom.

All other radiometric quantities derive from this. In particular, the various irradiances are derived by weighted integration of the radiance field over defined

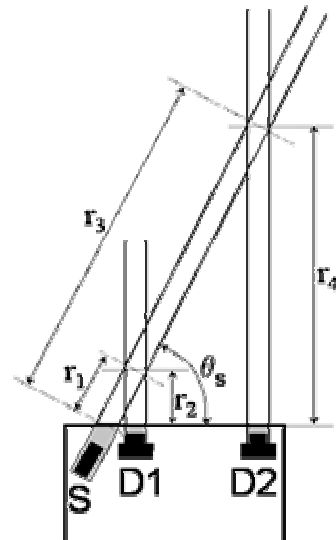


Figure 2. Sensor for determining c from two measurements of backscattering at the same angle (see text). S is the source, and D1 and D2 are photodiode detectors. The effective pathlength is $(r_3+r_4)-(r_1+r_2)$.

solid angles. The downwelling ($E_D(\lambda)$, units of $\text{W m}^{-2} \text{nm}^{-1}$) and upwelling ($E_U(\lambda)$, units of $\text{W m}^{-2} \text{nm}^{-1}$) irradiances are given as the cosine-weighted integration of the radiance distribution over the upper (downwelling) and lower (upwelling) hemispheres, respectively. These hemispheres are separated by a horizontal surface oriented normal to the local gravity vector. The net downward irradiance ($E_N(\lambda)$, units of $\text{W m}^{-2} \text{nm}^{-1}$) represents the vertical component of the irradiance vector and is given by the difference between the upward and downward irradiances, or the cosine weighted integral over all solid angles. A further quantity of biogeochemical and physical interest is the scalar irradiance ($E_o(\lambda)$, units of $\text{W m}^{-2} \text{nm}^{-1}$) which results from the unweighted integration of radiance over all hemispheres.

A particularly useful relationship results from the integration of the radiative transfer equation to yield the Gershun equation. This (in the absence of transpectral processes such as fluorescence and Raman scattering, and in the absence of horizontal gradients) equates the vertical derivative of $E_N(\lambda)$ divided by $E_o(\lambda)$ to the absorption coefficient. This illustrates one example of how the radiative transfer equation can be employed to relate apparent and inherent optical properties; it is of further interest since the absorption coefficient so-determined controls both the local rate of thermal heating, and the absorbed energy available to drive local photochemical reactions such as photosynthesis. **[should this come after the introduction of K, near the “quasi-IOP” paragraph below?]**

Another derived quantity of interest results from spectral integration over the wavebands active in photosynthesis, generally taken as the interval from 350 or 400 nm to 700 or 750 nm. All of the above irradiances can be so-integrated, to provide a measurement of the so-called “Photosynthetically Available Radiation” (PAR, units of W m^{-2} or $\text{quanta s}^{-1} \text{m}^{-2}$). **[is usually only scalar?]**

For remote sensing, measurements of radiance and irradiance (see below) taken in water must be related to remotely sensed above-water radiances (see **Eq. 1**). To do this requires consideration of two factors, first the propagation of measurements taken at depth to the surface, and second the propagation of radiance across the sea-air boundary. The second is more straightforward than the first:

$$L_w(0^+, \theta, \Phi, \lambda) = L_u(0^-, \theta', \Phi, \lambda) \frac{1 - \rho(\theta, \theta')}{n^2},$$

where the water-leaving radiance just above the water (0^+) in a given direction (θ, Φ) derives from an upwelling below water (0^-) radiance stream of direction (θ', Φ).

The two streams are related through Snell’s law, $\theta' = \sin^{-1}\left(\frac{\sin \theta}{n}\right)$. The index of

refraction, n , is actually an inherent optical property (the real part of the complex refractive index) and is dependent on salinity and (weakly) on temperature and pressure. The reflection of the air water interface is given by ρ ; note that $\rho = 1$ for incident angles greater than the critical angle $\sim 48^\circ$ for $n = 1.34$. Note as well that this relationship presumes no transpectral scattering (e.g., water Raman effects).

Most of the historical work has assumed $\theta, \theta' = 0$, i.e. nadir viewing geometry **[I thought this was 180 deg? Guess it depends on coordinate system]**. In this special case, $L_w(0^+, 0, 0, \lambda) \approx 0.55 L_u(0^-, 0, 0, \lambda)$. However, most remote sensing instruments view

the ocean surface at angles removed from nadir. Furthermore, the Fresnel scattering of downward radiance from the ocean surface upward is a strong function of illumination and viewing geometry. These so-called bi-directional characteristics of the radiance field incident on the sensor on orbit are therefore considerably more complicated. A rather complete theoretical analysis of this can be found in Morel and Gentili (1996) and Mueller (2003); full evaluation of the bi-directionality of the radiance field below and above the sea-surface will require the routine measurement of the full radiance field (e.g. Morel et al. 1995; Voss et al. 2003; see below).

A more problematic situation occurs when radiance measurements taken at depth are required to be propagated to the sea-surface to estimate $L_u(0^-,0,0,\lambda)$ (in practice, nadir viewing instruments are usually employed, but in principle, the full radiance distribution could be used as well). It is rarely possible or even feasible to measure L_u accurately near the sea-surface (i.e., 0^-), given the presence of surface waves of various scales, and typically, reliable measurements have only been made for depths $z > \sim 1-2$ meters in the open ocean. More recent instruments provide accurate statistics of upwelling radiance at depths ~ 10 cm, at least for moderate sea-states (see below).

Given an accurate measurement of radiance at a range of depths, the problem faced is the extrapolation to just below the sea surface. The usual approach is to assume homogeneity over the upper ocean in some sense, and compute $L_u(0^-,0,0,\lambda)$ as (nadir assumed):

$$L_u(0^-, \lambda) = L_u(z_o, \lambda) \exp[K_L(z_o, \lambda)z_o],$$

where z_o is a reference depth below the surface, and K_L is the diffuse spectral attenuation coefficient for radiance at depth z_o (assumed constant over the interval 0^- to z_o). The diffuse attenuation coefficient is operationally derived from the derivative of the neperian log of the vertical radiance profile; analogous terms can be computed for L at arbitrary angles away from nadir, or for the various irradiances.

Note that the diffuse attenuation coefficient is derived from apparent optical properties, and therefore is itself an AOP. The rapid modification **[Marlon: not sure what you mean here - which error is this?]** of the radiance distribution in the upper optical depth, even with constant IOPs, implies that the assumption of homogeneity is almost assuredly invalidated; careful measurements well-resolved in the vertical and taken near the sea-surface minimize this error, at least in the absence of significant surface roughness. At longer wavelengths (>650 nm), the strong attenuation of water conspires with increased instrument shading, fluorescence and Raman scattering to render this extrapolation extremely tenuous.

In addition to providing a means to extrapolate radiances (and irradiances) within the upper ocean, the diffuse attenuation coefficients themselves are of considerable interest. Often viewed as “quasi-inherent” optical properties (e.g., Morel 1988, Gordon et al. 1988; Morel and Maritorena 2001), the close correspondence between K and the absorption coefficient places variations in K central to a wide range of applications, including the computation of photosynthesis (regulates the penetration of irradiance available for photosynthesis, as well as light absorbed; e.g., Behrenfeld and Falkowski 1997), the computation of local heating rates due to absorption of solar radiation (e.g., Lewis et al. 1990), the photochemical degradation of organic matter (e.g., Johannessen

et al., in press), lidar system performance (e.g., Allocca et al. 2002), and underwater visibility (e.g., Zaneveld and Pegau 2003).

Remote sensing applications often derive K as an output product from measurements of normalized water-leaving radiances through empirical and semi-empirical approaches. For example, K can be decomposed into component contributions as with the IOPs in **Eqs. 5-7**, and can be used as diagnostics for constituents in the ocean, in particular the derivation of chlorophyll concentrations in oceanic case I waters (see Morel 1988; Gordon et al. 1988; Morel and Maritorena 2001).

The above sections deal with variations in apparent optical properties in the ocean interior, and their propagation to and through the sea-surface for the estimation of the water-leaving radiances required for calibration and validation of sensors on orbit. As an alternative approach, measurements of upwelling radiance can be made above the sea-surface from ship, buoy or tower platforms. Such measurements are appealing in principle, as they provide a direct measurement of radiance leaving the ocean, and are free from errors in propagation in the upper layer. However, in addition to the desired water-leaving photons, such measurements suffer from the inclusion of photons reflected off the sea-surface. This Fresnel reflectance includes both radiance resulting from the direct reflection of the Sun, and from sky reflectance.

For all but the calmest of seas, the contribution from surface reflectance is complex, and can often overwhelm the water-leaving signal (see full discussion in Mobley 1999). For a flat sea-surface and uniform sky radiance distribution, it is straightforward to compute the Fresnel reflectance over a small subtended solid angle looking down at the sea-surface; it is the downwelling radiance at equivalent relative azimuth and at the complementary zenith angle, multiplied by the Fresnel reflectance, which varies with respect to zenith angle from ~ 0.02 for normal incidence to ~ 0.03 at 40° and then increases strongly with increasing angle in a well-behaved, and well-known manner.

In practice, even the lightest of winds ruffle the sea-surface, and uniform sky conditions are rarely encountered, except in heavily overcast days which are not of relevance to remote sensing applications as the sea-surface cannot be viewed from above. The physics are known; the difficulty is in the measurement (or in reality, parameterization) of the convolution of the sea-surface slope spectra (relative to the field of view) with the full sky radiance distribution, and the appropriate time-integration of the resulting at-sensor radiance time-series. With careful attention to detail, and under conditions approaching ideal, correspondence between water-leaving radiances determined from in-water approaches and above water measurements can be as good as 5%; under most realistic conditions, deviations $>20\%$ are more common. Current measurement approaches to the estimation of water-leaving radiances from above water platforms and their caveats are discussed in Mueller et al. 2003.

2.2.2 In-water measurement of AOPs

The measurement of radiance and irradiance, and the derivation of the diffuse attenuation coefficient and reflectances, have been extensively examined by the oceanographic community and has resulted in a detailed set of protocols and approaches for design, characterization, calibration, at-sea deployment, and data analyses of instruments for the measurement of ocean AOPs.

For the majority, these are “passive” instruments that rely on the measurement of radiances resulting from the solar beam, and which have been transmitted and

scattered/absorbed by the atmosphere, the sea-surface and the ocean interior. The instruments consist of a set of front-end optics which capture the ambient radiances, a means to filter or disperse the broadband radiances into more or less narrow spectral intervals, detectors which transform the impinging photon energy into electrical signals, and signal processing electronics which condition and digitise the resulting electrical variations into a digital data stream for further analysis.

The front-end optics are fixed depending on the measurement desired. For the measurement of the fundamental radiances, a series of stops or Gershun tubes are generally employed to define the subtended field of view (FOV) of the sensor; typical half angles are 10 degrees to 1.5 degrees. Trade-offs between desired narrow FOVs and signal strength/integration time in dark ocean waters are necessary.

For the measurement of irradiances, a variety of collector designs are used. For the measurement of downwelling ($E_D(\lambda)$) and upwelling ($E_U(\lambda)$) irradiances, a diffuser plate is generally used to weight the impinging photons by the cosine of their angle with respect to the surface of the collector. For scalar irradiances, collectors are designed as hemispheres or spheres which weight all incoming photons equally, regardless of the angle of incidence.

Most existing instruments measure a restricted angular distribution, typically downward/upward irradiances, and nadir-viewing radiances. Ideally however, one would like to measure the full radiance distribution, and compute the various irradiances directly from this. Furthermore, and in principle, the change in depth of the radiance distribution should provide sufficient information to not only derive the various irradiances (and associated diffuse attenuation coefficients and reflectances) through integration, but the absorption coefficient and the volume scattering function as well through inversion methods (e.g., Aas and Højerslev 1999). This type of sensor is particularly of interest in optically shallow regions, where the radiance distribution is strongly modified by interactions with the sea-bottom (see Voss et al. 2003). Although such instruments were used extensively in the 1960's, their complexity and high data rate requirements have meant that very few, apart from the work of Voss, are routinely deployed.

For decomposition of the broadband field into spectral intervals, two fundamental approaches have been taken. For defined wavelength bands, the most effective approach is the use of high-quality Ion Assisted Deposition (IAD) filters which exhibit low levels of fluorescence. These can be manufactured to defined spectral transmittances (albeit at some cost) and can be practically matched to the wavebands of the various satellite sensors for highest accuracy in calibration and validation. Matching diffusers can then be used which are optimised for cosine (or other) response at the center wavelength of these filters. Cut-off filters can be stacked to reduce the out-of-band response to very small levels ($<10^{-6}$). Typically, instruments are manufactured with 1 to 14 defined spectral channels, each carefully chosen for a specific application.

Alternatively, spectral dispersion can be accomplished by prism or grating approaches, and the dispersed beam imaged onto an array of detectors. Finer wavelength resolution and increased spectral channels ($\sim 128 \rightarrow 256$) can be achieved; these instruments are generally labelled as "hyperspectral" in nature. However, trade-offs arise due to the limited number of photons in the small spectral bands and care must be taken to minimize second-order out-of-band performance. As a general rule, radiometric specifications and performance of hyperspectral instruments are not as

rigorous as those for precision filter-based instruments, although the increased spectral resolution confers significant advantages for some applications.

With respect to detectors and associated electronics, a key metric is the signal to noise ratio which must be achieved over the high dynamic range required to cover the range of ocean conditions. Dynamic ranges of >18 bits can be achieved with individual silicon photodetectors; this results in a capability to profile irradiance reliably to the equivalent depth of the 0.01% light level under cloudy skies, while maintaining a high sampling frequency (6-10 Hz). Hyperspectral instruments, because of their nature and the reduced photon flux into narrow spectral bands, are not as capable, and generally rely on longer integration times (upwards of 8 seconds) to achieve equivalent signal to noise performance.

The accurate characterization of these sensors with respect to FOV (or cosine response), to spectral response, to thermal and pressure variations, to linear response to variations in incident radiance, and to signal to noise is essential. This is in addition to the requirements for instrument calibration. A large body of information on this extensive subject can be found in Mueller et al. (2003) and references found therein. For AOP measurements, a significant advantage is the existence of national standards of irradiance which provide a reference to which instruments anywhere in the world and at any time can be calibrated and intercompared with a high degree of confidence. Measurements of radiance, of attenuation, and of reflectance can thus be regarded as accurate measurements of a physical quantity, which can be rigorously compared over all time/space scales, including those comparisons with similar instruments onboard space-based platforms.

AOP instruments can now be manufactured with a very small form factor, and as with the IOP instruments described above, can be deployed on a range of platforms for the measurement of the apparent optical properties of the ocean, including new autonomous profilers and gliders.

2.3 BIOGEOCHEMICAL PROPERTIES

The ultimate objective of most remote sensing algorithms is usually to derive some biogeochemical property from R_{rs} . For the majority of remote sensing algorithms, this derived biogeochemical property is chlorophyll concentration. As discussed earlier, algorithms also exist to derive an extensive and continually growing list of other biogeochemical properties.

So what in-water analytical instrumentation is available to measure these properties? With few exceptions, in-situ determination (using optical or other analytical methods) of biogeochemical properties at accuracies suitable for remote sensing validation work constitutes one of the largest gaps in currently available instrumentation. For example, while all of the properties in **Table 1** can be estimated from IOPs and/or AOPs with simple empirical relationships, the relationships are not robust, particularly in coastal case 2 waters, because of the wide variability in the composition and relative concentrations of the dissolved and particulate components of seawater. It is out of the scope of this work to detail the specific problems associated with in-situ optical characterizations of each property. The important point is that essentially all methodologies for determining biogeochemical parameters with an analytical precision and accuracy suitable for remote sensing applications are laboratory-based at this time. The lack of suitable, automated, in-situ instrumentation for biogeochemical parameters

can thus be considered a substantial hindrance to future algorithm development and validation efforts.

It may be argued that one emerging exception may be in-situ methodologies for determining nutrients (Johnson and Coletti 2002, Hanson and Donaghay 1998, Hanson 2000), but these techniques are new and have not been rigorously validated. The Johnson and Coletti (2002) technique determines nitrate via hyperspectral measurements of UV absorption. The Hanson and Donaghay (1998) method determines up to eight different nutrients simultaneously using “wet chemistry,” or the in-situ addition of chromophoric reagents that produce a color (or fluorescence in the case of ammonia) in proportion to the concentration of the nutrient. This latter device is essentially a submersible, digitized autoanalyser.

3 Platforms

In the last several years, an exciting variety of deployment platforms for in-water oceanographic instrumentation have been developed that complement more conventional ship-based measurements. Each platform has a unique niche in terms of the temporal and spatial coverage it provides. Sampling strategies that integrate multiple platforms can therefore be very effective in studying biogeochemical phenomena ranging over large time and space scales (Dickey et al. 2004). This section describes the general types of platforms available and provides some examples of using these platforms for remote sensing related applications.

Obtaining high quality in-situ optical and biogeochemical data for remote sensing algorithm development and validation can be challenging. In addition to the obvious challenges associated with making accurate measurements on relevant time and space scales, the ocean is inherently a difficult environment to conduct research. Autonomous platforms must contend with occasionally violent weather (e.g., Chang et al. 2001), biological fouling of sensors (e.g., Chavez et al. 2000), various obstacles (e.g., bathymetry and ships), and must rely on wireless communications to send their data and receive instructions or be situated sufficiently close to shore that cabled power and communications can be run to the platform. The ocean environment is also highly corrosive to a wide range of materials. Sensors for these platforms must be compact and have low power requirements. And there is always the challenge of making the needed measurements at a reasonable cost. Nonetheless, it will be apparent in the following that platform technology development efforts have been and continue to be highly successful despite these obstacles.

3.1 STATIONARY VERTICAL PROFILERS

The most common method of in-situ sampling is vertical profiling from a boat or ship (**Fig 3**). Sensors are typically secured in a cage and interfaced with a central data handler/controller that records and time stamps the separate data streams. Power can be provided with underwater batteries and data can be logged on the profiler for downloading later. Alternatively, a cable can be used for data and power to allow real-time viewing at the surface. Ballast is often added to a profiler to bring the net weight underwater near neutral (**Fig. 3a**). This enables a slow descent rate when free-falling in order to resolve vertical finestructure.

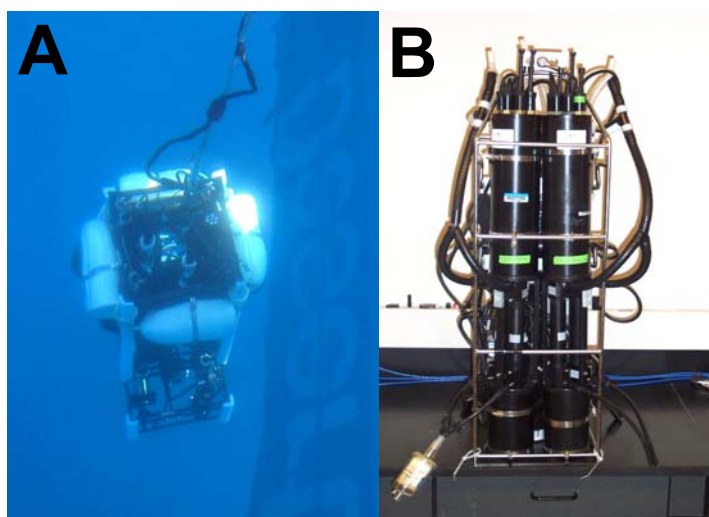


Figure 3. (A) A vertical profiling system deployed in Lake Tahoe from a Desert Research Institute vessel in 2003; (B) a vertical profiler in preparation for work in the field. The picture in (B) shows a configuration for simultaneously measuring the dissolved and particulate a and c components of seawater (particle filter attached to intakes of the meter on the left).

There are some considerations when measuring AOPs from a ship. Potential shading/reflection effects from the ship (Waters et al. 1990) and the package itself (Leathers et al. 2000) must be avoided if possible. AOP profiling systems consequently have been developed that allow for profiling several hundred feet from a ship (Fig. 4). For remote sensing validation work, typically radiance and irradiance sensors are oriented down-looking and up-looking, respectively, in order to obtain L_u and E_d .

Stationary vertical profiling can provide excellent resolution of the vertical structure of optical properties in the water column (e.g., Donaghay et al. 1992; Twardowski et al. 1999; Fig. 5). Data are usually of the highest quality because cleaning of the optical windows and calibration protocols can be performed on a regular basis. Issues such as power, instrument size, data volume, etc. are also typically not concerns. Profiling from a ship has the added benefit that discrete samples can be concurrently collected for laboratory analyses of biogeochemical properties. For these reasons – as well as the unavailability of other suitable platforms – the vast majority of data sets for remote sensing algorithm work over the years have been collected from ships.

While optical and biogeochemical data collected from ships have been enormously useful in remote sensing applications, there are some important limitations. The first is the relatively high cost, and the second is the time-space domain covered with vertical profiling data from a typical cruise is somewhat restricted. Nonetheless, in the foreseeable future it is difficult to envision a sampling strategy for remote sensing algorithm development or validation work that does not heavily rely on vertical profiling from ships.

Interestingly, optical profiling systems have also been deployed from land-water planes (A. Petrenko, personal communication, 1998) and via helicopter during the 1997-1998 European COAST/OOC (coastal surveillance through observation of ocean color)

campaign (**Fig. 6**). Such aerial platforms are able to sample stations over large spatial ranges more rapidly than is possible with boats.

Autonomous moored profiling technologies have been available since the 1970s (e.g. Brown et al., 1971; Van Leer et al., 1974). Systems have employed a variety of possible techniques to profile, but buoyancy manipulations or winches have primarily been used. Operating power has been supplied by batteries, onshore cable, and even wind-driven generators. Current incarnations still use these traversal mechanisms (e.g. Provost and du Chaffaut, 1996; Reynolds-Fleming, et al., 2002). In addition, energy from ocean currents and surface waves has also been harnessed to vertically propel the sensor package (Echert et al., 1989; Rainville and Pinkel, 2001, respectively).

A drawback of the above designs is the fixed presence of a mooring wire and a surface or sub-surface buoy. Surface expression is also a concern in coastal research applications because it can invite vandalism. These problems can be avoided by adopting a bottom-mounted winch design, such as the LEO-15 vertical profiler (Purcell, et al., 1997). This system, however, is large (3 x 3 x 1.5 m) and requires a permanent onshore cable for power and data transfer. A cabled underwater winch system with much smaller size will be deployed at the Bonne Bay Cabled Ocean Observatory in Newfoundland (**MARLON: REF ******).

A compact, fully automated profiler termed the Ocean Response Coastal Analysis System (ORCAS) has also recently been developed to resolve finescale vertical structure (Donaghay et al. 2002). This system is designed for shallow water coastal environments and has a sophisticated suite of IOP and AOP sensors. While still not a mature technology, Donaghay et al. (2002) have deployed multiple ORCAS profilers in a network to sample 4-dimensional structure in optical properties with very promising results. This work demonstrates the concept of using arrays of platforms separated at critical scales needed to resolve coastal biogeochemical phenomena and extrapolate to the larger picture.

The Shallow-water Environmental Profiler in Trawl-safe, Real-time configuration (SEPTR) developed by the NATO SACLANT Undersea Research Centre and the University of Rhode Island (Tyce et al., 2000) is another profiler with no surface expression. It consists of a saucer-shaped, trawl-resistant shell (2.0 m diameter at base x 0.5 m height) that encases an Acoustic Doppler Current Profiler (ADCP) and a winch-driven, bottom-up profiling capsule, as well as the associated control electronics and batteries. While the SEPTR profiler has been successfully used in many coastal environments, it has a small payload capacity limiting its utility for remote sensing calibration/validation research. Trawl-resistant structures are critical for coastal autonomous profilers.

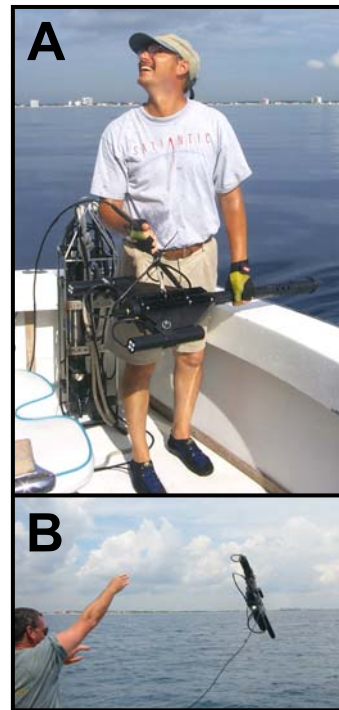


Figure 4. (A) AOP profiling package and (B) its deployment. A. Weidemann in (A), M. Lewis in (B).

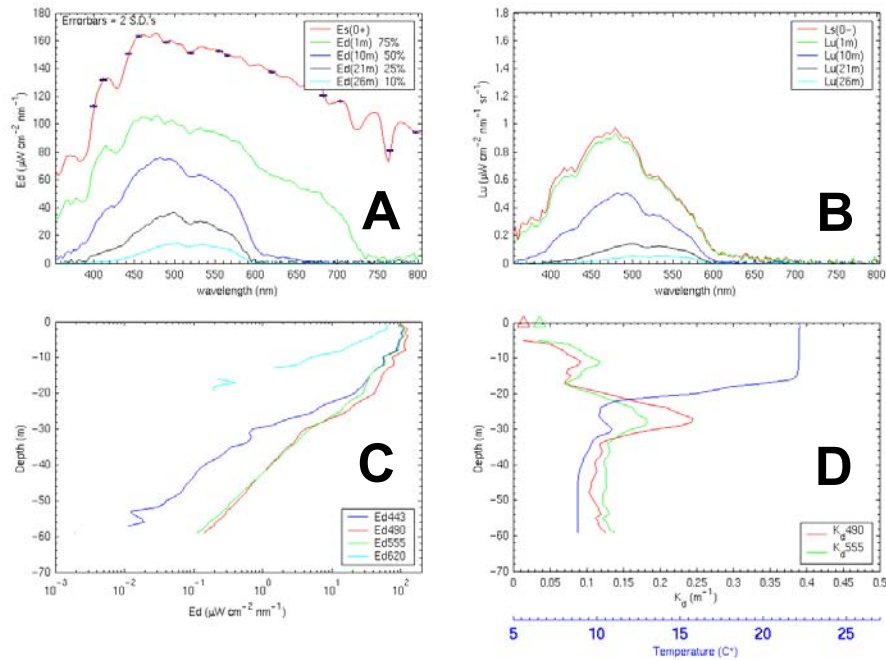


Figure 5. (A) Spectral downwelling irradiance and (B) spectral upwelling radiance at selected depths; vertical profiles of (C) irradiance and (D) the diffuse attenuation coefficients. Collected in the Northwest Atlantic, August 2001. Note plankton layer centered at ~28 m.

Other commercially available moored profiling system designs incorporate a bottom-mounted winch with a slip ring for transfer of power and data to and from the sensor package. This design makes the package vulnerable to several hazards, including rotation which ultimately applies excess torsional stress on the cable. Importantly, bottom-mounted winch profiling systems are highly susceptible to surface wave heights which alternatively produce conditions of sudden slack and tension in the cable. These systems are also large and heavy, with individual platforms for the winch and data system increasing the complexity of the deployment and recovery. Furthermore, the power requirements of these systems including winch are demanding (more than 100 Watts).

Because of these obstacles, autonomous stationary profiling technology is not mature or operational at this time. The critical current challenges are managing power needs and sustaining reliability for autonomous deployments of 6 months or more. Because of their ability to resolve dynamic vertical structure in coastal waters, these platforms hold particular promise for remote sensing case 2 algorithm development and validation pursuits.

3.2 FLOW-THROUGH SYSTEMS

Most research ships have built-in flow-through systems that continuously circulate water collected a few meters from the surface through on-board laboratories. These systems readily allow the installation of IOP sensors for making continuous

measurements while underway. Effective flow-through systems with optical sensors can also be developed for small boats more appropriate for near-shore coastal research (R. Arnone and R. Gould, personal communication, 2000) or for ferries or ships of opportunity (Schroeder and Petersen 2000; Balch et al. in press).

Optical data from flow-through systems effectively resolve small horizontal scales that stationary vertical profiling systems cannot (Pegau et al. 2000). Surface data are also the most critical for remote sensing algorithm work, although the underlying vertical structure of optical properties through the euphotic zone along the ship track is required for rigorous comparisons. One of the principle benefits of a flow-through system is the capability to use sensitive bench top instruments that have no submersible analogues.

3.3 TOWED VEHICLES

Since the backscattered signals collected by passive and active remote sensing systems are dependent on the vertical structure of optical properties along the flight path, sufficient resolution in both the vertical and horizontal dimensions are needed to develop effective algorithms for remote sensing applications. While stationary profiling from ships and continuous flow-through systems provide complementary vertical-horizontal coverage, the vertical dimension remains unsampled while underway.

One solution to the problem of synoptically sampling horizontal and vertical dimensions is to use an undulating towed vehicle (Barth and Bogucki 2000; Hales et al. 2001; Miller et al. 2003). Such a system is able to provide a continuous series of data points for remote sensing applications where transect lines can follow the flight paths of a remote sensor. Large data sets of relevant optical properties aligned with remotely sensed signals can therefore be collected. Historically, the use of towed systems for underway sampling with optical sensors has been pioneered by the Continuous Plankton Recorder (e.g. Hays and Lindley 1994) and follow-on systems (Aiken and Bellan 1990).

A towed system specifically developed for remote sensing applications was described by Miller et al. (2003) (Fig. 7). While underway, the towed package can be programmed to automatically undulate through the water column between specified depths. The vehicle is equipped with an *a* and *c* meter, backscatter sensors, fluorometers, a conductivity-temperature-depth (CTD) sensor, and can also be configured with irradiance and radiance sensors. The vehicle and tow cable were designed with a built-in discrete water sampling system, where samples are pumped



Figure 6. Vertical profiling from a helicopter during the COAST/OOC campaign. Courtesy of M. Babin.

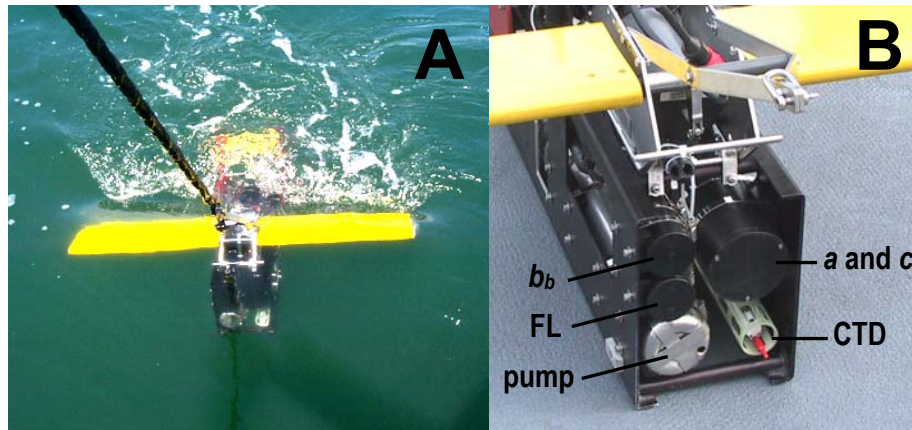


Figure 7. (A) A towed vehicle with on-board optical sensors completing a transect, and (B) a close-up of the front of the sensor cage showing backscattering and fluorescence meters, the pump for pumping samples continually to the surface, the end can of an a and c meter, and the CTD.

continuously from the vehicle through a hose embedded in the tow cable to the boat. Consequently, the system allows concurrent collection of in-water optical data and discrete sampling for laboratory analyses of biogeochemical properties synoptically in the vertical and horizontal along the ship track (**Fig. 8**).

While such towed systems are well-suited for remote sensing applications, they still require the use of ships and the associated expense. In coastal regions, however, these systems can be deployed from relatively small boats (less than 10 m) that are inexpensive to operate. The costs in using towed systems for periodic synoptic sampling of coastal regions may therefore be practical in many cases.

3.4 MOORED PLATFORMS

Until recently, moored sensor systems have been the primary means by which long-term, high-frequency optical data have been collected (e.g., Dickey et al. 2004). These fixed position, or Eulerian, platforms provide data streams synoptically with respect to time that match up with satellite-based imagers. Hazardous weather conditions that would normally restrict conventional ship sampling does not affect the performance of properly constructed moorings (Chang et al. 2001). Moored sensors are thus well-suited for calibration and validation of remotely sensed signals (Clark et al. 1997; Pinkerton and Aiken 1999; Zibordi et al. 2002; Antoine and Guevel, 2000).

While several moored sensor systems have been deployed in the more classical oceanic case 1 remote sensing environments (Clark et al., 1997; Chavez et al., 1999; Dickey et al., 1998, 2001), few have been deployed in more optically complex case 2 environments. This has been primarily due to a programmatic emphasis on characterizing the open ocean surface waters using global ocean color imagers. Adapting this technology to the optically diverse and productive nature of most coastal water environments presents additional challenges on the design and use of moored sensor systems. For example, coastal waters are regions of high vertical and horizontal

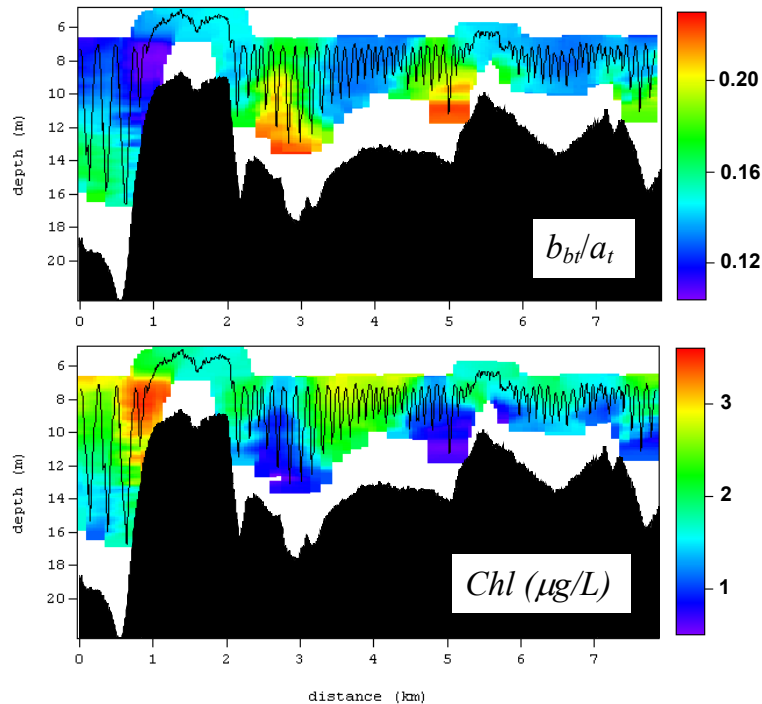


Figure 8. The backscattering to absorption ratio and chlorophyll concentration from fluorescence measurements collected with a towed vehicle platform in Narragansett Bay, RI. The vehicle was programmed to automatically undulate within the range of 5 m from the surface and bottom.

optical variability in comparison to most open ocean environments. In order to fully resolve this variability, coastal mooring systems require an increase in the number of optical sensors in the upper water column (to resolve vertical structure) as well as an increase in the temporal sampling (to resolve small scale horizontal variability).

Much progress has been made in using moored optical sensor systems for remote sensing ocean color algorithm development for coastal waters. This has been due to recent advances associated with the miniaturization of optical sensors and the development of anti-biofouling devices and methodologies (Dickey et al., 2001, 2003). Optical sensing systems deployed in coastal regions are highly susceptible to the build up of organic matter and organism growth and settling, or biofouling (**Fig. 9**). In order to ensure data integrity, optical sensors on coastal moorings must be serviced frequently (order of months) and must include biofouling prevention strategies (McLean et al., 1997; Chavez et al., 2000; Barnard and Roesler, 2003; Manov et al., 2003). The use of copper materials has recently been shown to be very effective in mitigating the effects of biofouling, allowing for deployments of up to six months and more for some optical sensors (Barnard and Roesler, 2003; Manov et al., 2003). Various optical sensors can be equipped with copper shutters mounted a few millimeters above the optical face. The slow release of copper ions through dissolution in seawater creates a toxic layer above the sensing face when the sensor is not in use. During sampling, the copper shutter

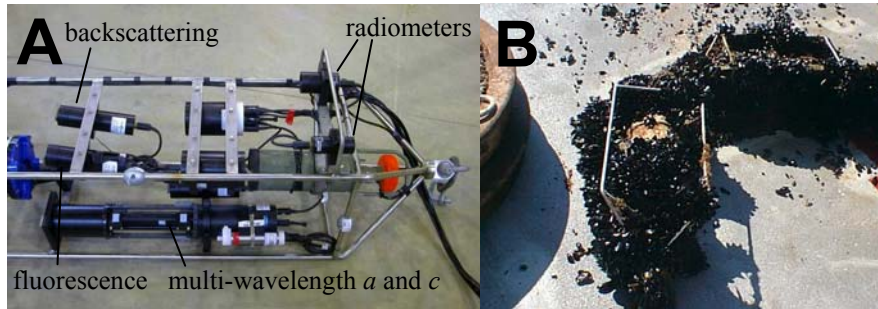


Figure 9. Biofouling of optical sensors at GoMOOS after 5 months at sea. (A) before; (B) after (picture taken in 2002).

rotates 180 degrees, exposing the optical face. Copper shutters are effective but can be susceptible to mechanical failures due to growth of large marine organisms on or near the shutter that impede the rotation of the shutter. To prevent marine organisms from attaching, various copper materials such as foil tape can be applied to the sensor.

Technological advances such as these have led to the recent proliferation of optical sensing systems in a variety of research and environmental monitoring mooring programs. One such program is the Gulf of Maine Ocean Observing System (GoMOOS; www.gomooos.org). The primary purpose of the in-situ bio-optical component of the Gulf of Maine Ocean Observing System (GoMOOS) mooring program is to provide hourly observations of biogeochemical parameters related to ocean productivity, water clarity, and ecosystem community dynamics. A secondary goal was to provide in situ measurements that could be used to aid interpretations of ocean color remote sensing imagery. GoMOOS operates and maintains four moorings equipped with bio-optical instrumentation in the coastal regions of the Gulf of Maine. Two of these moorings contain a robust suite of optical instrumentation near the surface providing radiometric and bio-optical measurements including spectral upwelling radiance, spectral downwelling irradiance, spectral absorption, scattering, beam attenuation and volume backscattering and include anti-biofouling devices such as copper materials and shutters. Since 2001, the GoMOOS program has been providing hourly observations of surface optical and radiometric properties which have been used in combination with bio-optical models to develop and validate ocean color inversion algorithms (Barnard and Roesler 2003; Roesler and Barnard, 2003).

Measurements of normalized water leaving radiance at nadir taken from moored platforms have shown excellent agreement with comparable measurements taken from the SeaWiFS sensor as it passed over the mooring (Dickey et al. 2004) emphasizing the efficacy of such systems for calibration and validation of ocean color satellite sensors. Indeed, the primary means for on-orbit calibration and validation of SeaWiFS and MODIS has been the MOBY moored system (Clark 2003) and the European MERIS program relies on the BOUSSOLE mooring in the Mediterranean Sea (Antoine and Guevel 2000) which is now operational.

3.5 PROFILING FLOATS

Over the last few years, the ARGO program has begun to seed the world's oceans with Autonomous Profiling Explorer (APEX) floats (CLIVAR 1999; Wilson 2000).

Their goal is to have 3000 floats spaced in a ~300 km grid pattern covering the global ocean. As of October 2003, 947 floats had been deployed (C. Jones, personal communication, 2003). These floats are designed to “sleep” at a depth of 1000-2000 m, waking up every 7-10 days to make ascents to the surface while recording CTD measurements. Data is telemetered via satellite when at the surface. A variable buoyancy engine provides the negative and positive buoyancy required to profile. Expected lifetimes for APEX floats are 4-5 years on average. The Scripps Institute of Oceanography Instrument Development Group and the French IFREMER Marine Technology and Information Systems Division make APEX analogue floats called the Sounding Oceanographic Lagrangian Observer (SOLO) and PROVOR, respectively. Recent precursors to the APEX floats were the Autonomous Lagrangian Circulation Explorer (ALACE), and the profiling ALACE (PALACE) (Davis et al. 2001).

Primarily because of ARGO, profiling float platform technology has emerged as one of the most reliable and cost-effective available. To date, the APEX floats used in ARGO have provided a 79% reliability of data return (C. Jones, personal communication, 2003). Other cost-effective drifting profiling floats have also been developed for more coastal applications. Because of their relatively low cost, deploying arrays of floats to address remotely sensed biogeochemical phenomena occurring over large time and space scales can be a practical consideration. Since APEX floats spend the majority of their time out of the photic zone, biofouling is a minor consideration (Bishop et al. 2002). A key obstacle, however, is the availability of compact optical sensors with suitably low power requirements and data volume compatible with satellite communication bandwidths.

There are only a few instances where optical instruments have been deployed on profiling floats. One very effective deployment was carried out by Mitchell et al. (2000) in the Sea of Japan with a SOLO float outfitted with a 3-wavelength irradiance sensor. The float profiled the upper 400 m once every 2 d and data was presented over about a four month period. The float captured the onset of the spring bloom and the accompanying subsurface stratification. The K_d parameter could be determined for each irradiance profile and showed excellent agreement with the SeaWiFS K490 product. This study demonstrates the potential of expanding use of such platforms for synoptic remote sensing related applications.

In another recent study, Bishop et al. (2002) equipped an APEX with a customized beam attenuation meter to measure POC concentrations in the North Pacific. These floats, or “Carbon Explorers,” were able to resolve vertical distributions of POC over several months. Within the data records, enhanced carbon biomass from a natural iron “fertilization” event associated with an Asian dust storm was documented. It is exactly these kinds of episodic, short-lived phenomena that conventional ship sampling can only document with a great deal of luck. And there is a growing recognition that episodic events not easily sampled discretely from ships – short-lived, intense phytoplankton blooms, dust deposition events, and the passing of storms – may be driving forces behind the global cycling of carbon (Bishop et al. 2002; White et al. 2002; Dickey et al. 2004). Autonomous profiling technology may prove the ideal platform for studying such processes.

3.6 AUTOMATED UNDERWATER VEHICLES

An Autonomous Underwater Vehicle (AUV) provides its own propulsion to allow high-resolution sampling of the ocean's interior in the horizontal spatial dimension as well as the vertical. There are many types of AUVs (Griffiths et al. 2001), but they generally fall into two categories: self-propelled and gliding.

3.6.1 *Self-propelled vehicles*

Autonomous vehicles with propellers have been in development internationally for over 40 years (e.g., Blidberg 1991). They vary widely in size, depth rating, sensor payload space, rated operation duration, guidance systems, and telemetry modes. Propelled AUVs can rapidly cover relatively large vertical and horizontal regions. For example, the Remote Environmental Monitoring Units (REMUS) made by Hydroid, Inc. can cover 100 km in about 20 hours. While most propelled vehicles are still rather expensive to realize widespread use for oceanographic research (typically cost several US\$100,000), cost has come down substantially over the last several years. Some small AUVs that are produced in high volume, such as the "disposable" AUVs made by Sippican that are used as targets in military exercises, can be purchased for as little as a few thousand US\$.

Battery power with AUVs is currently one of the key limiting factors in their long-term use. Most propelled AUVs are thus designed for deployments of not more than a day or two. Efficient, energy dense storage technologies such as solid oxide fuel cells are currently a key development area (e.g., Singhal 2000). As an illustration of the current problem, one of the largest AUVs, the U.S. Navy's Seahorse, uses 9,216 common alkaline "C" batteries for power.

Optical sensors routinely used on propelled AUVs are backscatter sensors and chlorophyll fluorometers (e.g., Yu et al. 2002). Sophisticated spectral upwelling and downwelling radiometers have been integrated in a REMUS AUV and successfully deployed in a number of operating scenarios in coastal regions off New Jersey (Brown et al. 2004). In-situ "wet chemistry" nutrient analysers have also been adapted for AUV use (A. Hanson, personal communication, 2003).

Technology is currently being developed that will allow AUV networking and adaptive sampling so features of interest such as biological layers or river plumes can be intensively sampled. More advanced technologies such as node docking and equipment deployment capabilities are being pursued in industries such as oil exploration and cable laying that may be transferable to oceanographic studies in the future.

3.6.2 *Gliders*

Gliders are buoyancy regulated like APEX floats but use wings to convert vertical velocity into forward velocity. They are suitable for long duration sampling (weeks to months), usually following a "sawtooth" pattern. Although traveling velocity in the horizontal is relatively slow ($< 0.5 \text{ m s}^{-1}$), total distances traveled during a mission can be thousands of kilometers. A variety of two-way wireless communication methods are supported, including satellite-based Iridium. Because gliders can be programmed to surface on a frequent basis, their sampling mission can be altered at any time. Like propelled AUVs, technology enabling adaptive sampling is also in development.

Four primary glider technologies have been developed: the Slocum Littoral (Webb Research Corp), the Slocum Thermal (Webb Research Corp), the Spray (Scripps Institute of Oceanography), and the Seaglider (University of Washington). All use power from lithium or alkaline batteries except for the Slocum Thermal. The Thermal harnesses energy from a chemical change-of-state reaction that occurs from ambient temperature changes as it glides through the ocean's thermocline.

Like other autonomous platforms, power and size constraints are of paramount importance for sensors deployed on gliders. A non-technical problem with deployment of the Slocum Littoral glider has also been fishermen, who have picked up the platforms while they are at the surface transmitting data. **Fig. 10A** shows a deployment by the Rutgers glider team of a Slocum Littoral glider equipped with optical sensors (**Fig. 10B**) measuring spectral backscattering, fluorescence, and beam attenuation. The beam attenuation meter employs the recently developed dual-backscattering method described in **section 2.1.2**. Data from this sensor is shown in **Fig. 11**.

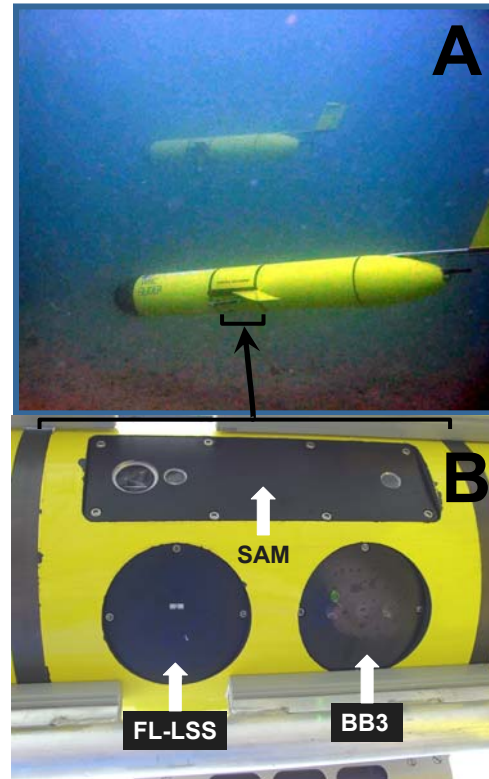


Figure 10. (A) Slocum Littoral gliders, and (B) optical sensors integrated in the payload compartment of the glider; SAM = Scattering-Attenuation Meter (see Fig. 2), BB3 = 3-wavelength backscattering sensor, and FL-LSS = DOM fluorescence and Light Scattering Sensor (broadly weighted side scatter). Photos courtesy of E. Creed and the Rutgers glider team.

3.7 DIVERS AND NEKTON

Divers have been used to collect optical data for remote sensing applications when the exact proximity of the sensing element and/or its intake is critical (Zaneveld et al. 2001; Dierssen et al. 2003; **Fig. 12**). Divers are often necessary when studying the optical properties of the bottom, such as in the validation of the leaf-area index for seagrasses (Dierssen et al. 2003). Optical phenomena that occur over very small spatial fields – e.g., the scattering properties of the sea-bottom, the particle attenuation around corals, or the absorption by dissolved materials in close proximity to seagrass beds or in sediment pore waters – can only be effectively sampled by divers (Zaneveld et al. 2001; Boss and Zaneveld 2003, Voss et al. 2003).

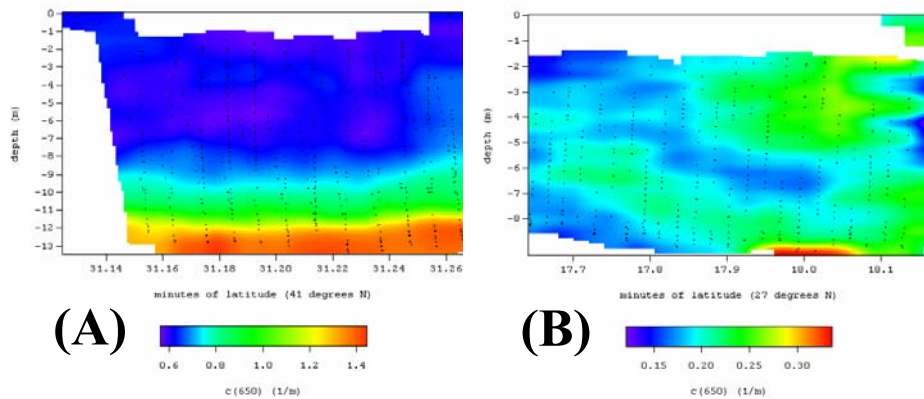


Figure 11. Attenuation data from a glider deployed by the Rutgers glider team off (A) Buzzards Bay, MA, August 19, 2003, and (B) the west Florida coast, November 6, 2003. Data was collected from the glider via wireless telemetry.

Finally, large fish and whales should be considered as possible platforms. The fisheries research community is already using light sensors on fish as a method of estimating geolocation (Sibert and Nielsen 2001). This work demonstrates that these platforms could perhaps be suitable for remote sensing related applications if the relevant in-situ sensing technology can be appropriately miniaturized.

4 Considering sampling strategy

The usefulness of in-water measurements with respect to remote sensing can be broken down into two broad categories: 1) helping interpret ocean color measurements from remote sensors, and 2) filling the gaps in data along time-space axes not resolved by remote sensors. While a detailed discussion of sampling strategies for these sets of applications is out of the scope of this review, some comments from a technology perspective may be useful.

Ocean color interpretations via algorithms require comprehensive data sets covering broad dynamic ranges of biogeochemical and optical properties. Often important endmember data points for these ranges can only be collected during short-lived, episodic events such as intense blooms (that may perhaps be harmful), dust deposition, and vigorous mixing from passing storms. These events are also usually the most interesting from a science perspective, and may be critical in understanding the more long term dynamics of ocean ecosystems. Conventional ship sampling is not well-suited to resolving such events. And on the serendipitous occasion such an event is observed, conditions before and after the event are rarely well documented. These observations lead to the conclusion that automated platforms should play a more significant role in ocean color work. Preliminary investigations strongly support this notion (Mitchell et al. 2000; Bishop et al. 2002; Barnard and Roesler 2003; Roesler and Barnard 2003).

The need for comprehensive data sets at reasonable cost also suggests that the implementation of in-situ instrumentation and techniques in ocean color sampling strategies should continue to be pressed. In-situ measurements typically have high sampling rates, are less labor-intensive than lab-based methods, and many can now be

made autonomously. There is, however, a fundamental lack of in-situ sensors for making measurements of the needed biogeochemical properties with the accuracy required for algorithm development and validation. Most biogeochemical analyses still need to be performed in the lab on discrete samples. The requirement to collect discrete samples is a significant obstacle to future algorithm development/validation efforts. Developing accurate in-situ biogeochemical sensing technology compatible with automated remote operation thus deserves astute attention by the oceanographic community.

At the present, the problem of sampling strategy is – whether we like it or not – at least constrained by several factors, including 1) the availability of instrument technology, 2) the availability of platform technology, and 3) cost. While the latter was not discussed in detail, by reviewing the first two factors we hope a better understanding of feasible sampling strategies for remote sensing applications may be realized. Areas where the programmatical top-down approaches to addressing global biogeochemical phenomena do not overlap with this more bottom-up approach should be the focus of development efforts in the future.

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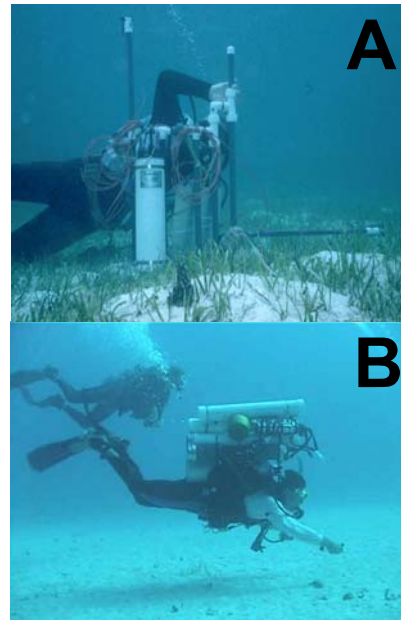


Figure 12. Diver-controlled in-situ measurement of (A) AOPs with a Diving Operated Benthic Bio-optical Spectrometer (DOBBS) and (B) IOPs with an a and c meter. Sensor intakes in (B) held in diver's right hand. Photo in (A) courtesy of H. Dierssen. Divers in (B) are Emmanuel Boss (foreground) and Ronald Zaneveld. Photo courtesy of E. Boss.

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