Chapter 4

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. 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 be resolved by an orbiting satellite imager. 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 cycling of carbon in the ocean and serve as indicators of ecosystem health. In-water measurements help elucidate the link between these components and the remotely sensed signal.

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 spectral upwelled water-leaving radiance, $L_u$ (W m$^{-2}$ nm$^{-1}$ sr$^{-1}$) and primarily consists of light scattered in the backward direction off the particles and molecules of seawater (for a complete discussion, refer to Zaneveld et al., Chapter 1). Sunlight incident at the ocean surface is represented as spectral downwelling surface irradiance, $E_d$ (W m$^{-2}$ nm$^{-1}$), and the so-called remote sensing reflectance, $R_{rs}$, is derived from $L_u/E_d$ with $L_u$ strictly defined in the nadir direction (normal to the plane of the ocean surface). Although $L_u$ 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 just below the ocean surface (represented as $0^\circ$) can be simply written (Morel and Prieur, 1977):

where the factor $\Psi$ varies within a relatively small range depending on surface illumination conditions and the volume scattering properties of the water body (Morel and Gentili, 1993; 1996). Each of the parameters in Eq. 1 have implicit spectral dependencies. Radiance and irradiance have units of W m$^{-2}$ sr$^{-1}$ and W m$^{-2}$, respectively, and spectral radiance and spectral irradiance have units of W m$^{-2}$ nm$^{-1}$ sr$^{-1}$ and W m$^{-2}$ nm$^{-1}$, respectively. For details see Mobley (1994).

Understanding how the different components of seawater alter the path of incident sunlight through backscattering and absorption is essential to using remotely sensed ocean color observations effectively. This is particularly apropos 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. Such algorithms are commonly known as inversions because the forward problem of 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), a multitude of algorithms 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; 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 measurement procedures – Hooker et al., 2002, Hooker and Morel, 2003). Measurements of $R_{rs}$ are also 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),
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Semi-analytical algorithms typically use an analytical model (e.g., Morel, 1980; 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), 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 U.S. Moderate Resolution Imaging Spectrometer (MODIS) sensors aboard the Terra and Aqua satellites can be viewed at several NASA web sites.

Some algorithms focus on retrieving only 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 modeling, general water type classifications, or other applications such as estimating diver visibility (Zaneveld and Pegau, 2003).

In the following sections, the in-water measurements and sensors used in remote sensing applications are discussed in more detail. Because the temporal and spatial characteristics of in situ field data relative to data collected by a remote sensor is of fundamental importance for biogeochemical algorithm development and validation, the various types of deployment platforms available to support these 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 the context of the information is intended to help 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 relationships between the AOPs and IOPs. Zaneveld et al. (Chapter 1) discuss these relationships in detail and provide definitions and backgrounds for the relevant AOPs.
and IOPs discussed in this section. The following summarizes sensor technologies for measuring these properties. Specific issues relating to the deployment of optical sensors in the field (e.g., biofouling) are addressed in section 3.

2.1 IN-WATER MEASUREMENT OF INHERENT OPTICAL PROPERTIES

Recent advances in optical instrumentation and methodologies now enable the in situ measurement of many of the dissolved and particulate fractional IOP components (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 (the $a_w$, $b_w$, $c_w$, and $b_{bw}$ terms from Zaneveld et al., Chapter 1) can be considered knowns in the visible range with small error (Morel, 1974; Pope and Fry, 1997). Since no current in situ method can physically separate phytoplankton and their pigments from other particles, the absorption and backscattering attributable to phytoplankton, $a_p$ and $b_{bp}$ respectively, must be derived from in situ bulk particulate measurements ($a_p$ and $b_{bp}$) using bio-optical spectral decomposition models (e.g., Roesler et al., 1989; Bricaud and Stramski, 1990; Carder et al., 1999).

The conventional methodology for measuring beam attenuation, $c$, is rooted in the relationship between $c$ and the loss in power of a collimated, unpolarized source due to attenuation ($d\Phi$) across an infinitesimally small pathlength (dl) of medium:

\[
c\Phi_0 = -\frac{d\Phi}{dl}, \tag{2}
\]

where $\Phi_0$ is the incident source power. This is a differential equation with solution:

\[
\Phi_c = \Phi_0 \exp \left( -\int_0^l c \, dl \right). \tag{3}
\]

If we are interested in the bulk value of $c$ in a medium over the pathlength $l$, then Eq. 3 reduces to $\Phi_c = \Phi_0 \exp(-cl)$. Thus, by measuring the power $\Phi$ of a collimated beam at two locations within a medium a distance $l$ apart, we can solve for $c$.

This is the principle by which conventional $c$ meters (also called transmissometers) function, although there are many details. One of the most important details is that collimating optics are required in front of the detector measuring $\Phi_c$. Collimating optics help to exclude scattered light in the near-forward direction, which is very important since the vast majority of scattered light is deflected into the first few degrees. Remember, the $\Phi_c$ we need should ideally be comprised of only the unaltered radiance from the incident collimated source beam. The theoretically ideal $c$ meter would therefore have an acceptance angle for scattered light of $-0^\circ$, but practically this is not possible because no light would reach the detector. All $c$ meters consequently suffer from errors due to the acceptance of some near-forward scattered light, with measured attenuation, $c_m$, related to true $c$ according to:

\[
c_m = c - 2\pi \int_0^{0.5} \sin(\theta)\beta(\theta)d\theta, \tag{4}
\]

where $\theta_d$ is the acceptance angle, and $\beta(\theta)$ the volume scattering function. Note the error term is a function of both meter design and the characteristics of the medium and therefore varies for different natural waters. Acceptance angles should be as small
possible while maintaining sufficient signal, although for $\theta < \sim 0.1^\circ$ turbulence from small refractive index discontinuities in water (Bogucki et al., 1999) can introduce undesirable noise.

There are several possible methodologies for the in situ measurement of absorption (e.g., Pegau et al., 1995), but the most popular is based on the reflective tube principle (Zaneveld et al., 1990; Kirk, 1992). In implementing this method, a collimated, unpolarized source is employed, as with the $c$ meter. The receiving end in this case, however, is designed to collect as much scattered light as possible. The optical path through the medium is surrounded by a glass reflective tube, which in turn is surrounded by air, effectively reflecting any scattered light out to $\sim 42^\circ$ back into the flow cell. The angle $42^\circ$ is the angle of total internal reflection between the glass-air interface. At the collection end, a diffuser and wide-area detector are then employed to gather as much of the light scattered by the medium as possible. Since most of the scattering in the ocean is near-forward, only a small amount of light is lost with a reflective tube device (on the order of 10%) and corrections exist to account for this (Zaneveld et al., 1994).

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). An example is the WET Labs AC9, measuring $a$ and $c$ over nine wavelengths in the visible at a sampling rate of 6 Hz using the methodologies described above. The $a$ and $c$ measurements are blanked to clean water, and thus the absorption and attenuation of the combined dissolved and particulate fractions, $a_{dg}$ and $c_{pg}$, respectively, are directly measured. Absorption only in the dissolved fraction, $a_d$, may also be measured by attaching a particle filter to the intake of the absorption tube (Twardowski et al., 1999; 2004). Scattering due to particles, $b_p$, can be derived by subtracting $a_{dg}$ from $c_{pg}$. Detailed protocols for using these measurements to obtain the non-water IOPs are described in Mueller et al. (2003). Periodic calibrations with pure water to account for instrument drift (Twardowski et al., 1999), and corrections for the temperature and salinity dependencies of pure water absorption (Pegau et al., 1997) are important aspects of the recommended protocols.

Modern electronics, and a relatively long 25 cm pathlength, allow the AC9 to achieve accuracies sufficient to resolve natural oceanic and coastal levels of $a$ and $c$ without the need for concentrating samples. Because the magnitudes of many oceanic and coastal IOPs are relatively low, the issue of sufficient accuracy has historically been a challenging problem. The relationship between accuracy and pathlength can be expressed as (Højerslev, 1994):

$$\text{accuracy} = \frac{dc}{c} = \frac{e^{dl}}{cl}dT,$$

where the $dT$ term represents the electronic noise of the instrument. The great utility of this relationship is that the function $[e^{dl}/cl]$ is at a minimum when the $cl$ term, known as the optical pathlength, is equal to one. Thus, in clear oceanic regions where attenuations can dip below 0.1 m$^{-1}$, pathlengths on the order of 10 m would be optimal. For the 25-cm pathlength AC9, accuracy is optimized for $a$ and $c$ values of $\sim 4$ m$^{-1}$. However, because of stable electronics that make $dT$ very small, the precision in AC9 measurements is $\sim 0.001$ m$^{-1}$, enabling IOP determinations in the clearest waters with accuracies on the order of a few percent (compared to $<0.05\%$ in more turbid coastal waters). Calibrations with clean water are very important in achieving these accuracies, as instrument drift introduces bias errors that require correction.
A next-generation, hyperspectral \( a \) and \( c \) device, the WET Labs ACS, 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, resulting in a total of 84 wavelengths. Increased spectral resolution helps to resolve all the spectral ranges required for algorithms relevant for current and future remote imagers. Sullivan et al. (2004) have been able to document naturally occurring hyperspectral structure in \( a \) and \( c \) with this device occurring over centimeter 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 \textit{Karenia brevis} through a \( 4^{th} \) 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 \textit{K. brevis} detection model (e.g., Schofield et al. 1999).

For measurements of backscattering, determinations of \( \beta(\theta) \) are made in the backward direction (Fig. 1A). Recalling from Zaneveld et al. (Chapter 1)

\[
\beta_b = 2\pi \int_{\pi/2}^{\pi} \sin(\theta)\beta(\theta)d\theta, \tag{6}
\]

backscattering coefficients can be derived using measured \( \beta(\theta) \) 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 as low as a few percent. With measurements at only one angle, \( \theta_m \), a “\( \chi \) factor” is used in the simplified relationship:

\[
b_b = \chi [2\pi \sin(\theta_m)\beta(\theta_m)]. \tag{7}
\]

To minimize errors in estimating \( b_b \) from one angle, Maffione and Dana (1997) and Boss and Pegau (2001) recommend measurements of \( \beta \) at \( \theta_m \) values of 140° and 117°, respectively. Small errors in deriving \( b_b \) from \( \beta(\theta_m) \) result from the observation that changes in the shape of \( \beta(\theta) \) at certain regions of the backward direction are compensated by changes elsewhere, i.e., the \( \beta(\theta_m) \) serves as a “pivot point” (Boss and

![Figure 1](image.png)

**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.
Pegau, 2001). Variability around this “pivot point” is largely a function of the contribution of scattering from particles relative to the water background. As a result, if the water component of $\beta(0)$ is removed (see Morel, 1974 for the $\beta(0)$ of pure water and seawater), the derivation of $b_0$ is thus simplified and can be more accurate, especially in clearer waters (Boss and Pegau, 2001). When removing the water contribution, the method involves the following basic steps to obtain total $b_0$ from $\beta(m)$ (see Boss et al., 2004): 1) remove $\beta(m)$ due to water; 2) compute $b_0$ for particles only using Eq. 7 and an appropriate $\chi_p$ for natural particle populations (see Boss and Pegau, 2001); and, 3) add in the $b_0$ for water.

Recent data suggests $\chi_p$ values may vary little for natural particle populations. For example, Sullivan et al. (submitted) observed excellent correlations between measurements of particulate scattering at three angles in the backward direction in a data set that included over a thousand 1-m binned samples from numerous Case 2 water types (linear relationship between $\beta(100^\circ)$ and $\beta(150^\circ)$ exhibited $r^2$ of 0.97). Consistency in relationships between $\beta$ values – i.e., a generally representative shape for particulate $\beta(0)$ in the backward direction – implies that a consistent set of $\chi_p$ values may be used for natural waters and also that the angle $\theta_m$ is not so important as long as an appropriate $\chi_p$ is applied.

Every measurement of $\beta$ at one $\theta$ in practice resolves a weighted portion of $\beta(0)$, where a weighting function, $W(\theta)$, describes the angular dependency for a scattering measurement based on the geometry of the sensor (e.g., source half-angle and detector field-of-view properties):

$$\bar{\beta}(\overline{\theta}, \Delta \theta) = \int_0^\theta \beta(\theta) W(\theta) d\theta.$$  

(8)

The reported $\beta$ angle of a scattering sensor ($\theta_m$ above) is typically the centroid angle, $\overline{\theta}$, defined by the shape of $W(\theta)$. For example, the weighting functions for the WET Labs ECO-VSF sensor measuring scattering at 100°, 125°, and 150° are provided in Fig. 1B.

Raw backscattering counts can be calibrated to volume scattering coefficients using 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 field studies, sensors calibrated with these methods have agreed within ~10% (Boss et al., 2004). Details of these protocols can be found in Mueller et al. (2003).

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 has the advantage of being independent of excitation and emission spectral bandwidths, and spectral resolution. 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. No in situ hyperspectral fluorometers are currently available, but one such device is currently in development with promising preliminary results (R. Miller of NASA Stennis Space Center, and C. Moore of WET Labs, pers. comm., 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 called the SAFire that employs 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). Another such device is 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 recently been made submersible with promising results as well (Sosik et al., 2002).

A recent focus in new sensor development has been optical sensors compatible with compact, autonomous deployment platforms (discussed in 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 led to the development of new methodologies for measuring IOPs and AOPs. One such sensor for determining attenuation uses two measurements of backscattering made at the same angle but over different pathlengths (Twardowski et al., 2002, 2003; 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:

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

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 IN-WATER MEASUREMENT OF APPARENT OPTICAL PROPERTIES

Measurements of radiance and irradiance, and the derivation of the diffuse attenuation coefficient and reflectances, have been extensively examined by the oceanographic community and have 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 incident solar beam directly transmitted and scattered 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, spectral filtering or dispersing component to separate the broadband radiances into more or less narrow spectral intervals, detectors which transform the impinging photon energy
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 $(r_3+r_4)-(r_1+r_2)$.

into electrical signals, and signal processing electronics which condition and digitize 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 or upward irradiances, and nadir-viewing radiances. Ideally however, one would like to measure the full radian ce distribution, and compute the various irradiances directly from this. Furthermore, and in principle, the change in depth of the radian ce 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 Hojerslev, 1999). This type of sensor is particularly of interest in optically shallow regions, where the radian ce distribution is strongly modified by sea-bottom interactions (Voss et al., 2003). Although such sensors 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 ($<10^{-5}$). 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 (~128 to >256) can be achieved with this methodology and 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 remote sensing applications. For example, semi-analytical algorithms that rely on spectral decomposition of IOP components from remote sensing reflectances can generally perform better with more spectral input parameters.

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 oceanic 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 $R_{ss}$. For a great many 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 biogeochemical properties directly? 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, Table 1 lists several biogeochemical properties that have been derived from optical properties that can be determined in situ. Nearly all these derivations have been accomplished via simple empirical relationships. The problem that arises is that many of these 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. For example, while good linear relationships between Total Suspended Matter (TSM) and $c_p$ or $b_p$ are observed at certain times and places in the world’s oceans, the relationship is strongly dependent on the size and refractive index distributions of the particles and is therefore variable. Other particle properties such as shape and internal structure can also affect these relationships. Babin et al. (2003) found a more than two-fold variability in the TSM-$b_p$ relationship in coastal waters around Europe. Empirical relationships between IOPs and components of TSM such as POM and POC are even more tenuous because it must also be assumed that the relative proportion of a particular TSM component is constant. This is a poor assumption in coastal waters, where POM : TSM varies from only a few percent to near 100% (Kratzer et al., 2000; Babin et al., 2003).

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. Chlorophyll, for instance, can be estimated from in situ fluorescence and/or absorption measurements, but because the concentration-normalized absorption and fluorescence quantum yield of chlorophyll packaged in cells varies, these estimates do not satisfy established standards for algorithm validation work (e.g., Mueller et al., 2003). The lack of suitable, automated, in situ instrumentation for biogeochemical parameters can thus be considered a substantial hindrance to algorithm development and validation efforts. For example, consider the potential benefits of a sensor with an in situ method for determining chlorophyll concentration with an accuracy comparable to laboratory extraction methods; and this sensor was deployed on a fleet of autonomous platforms collecting data for algorithm development and validation work throughout the world’s oceans. As we will see shortly, the autonomous platform technology is nearing maturity; the limitation is the in situ biogeochemical sensing technology. If more accurate models are developed in the future to derive these biogeochemical properties from measurements made by optical sensors, the benefit is two-fold. First, accurate, composition-nonspecific determinations of biogeochemical properties may then be made from optical sensors that can indeed be deployed on autonomous platforms in many cases. And second, more rigorous relationships between biogeochemical properties and the optical properties help us move toward potentially more accurate analytical-type remote sensing algorithms that are able to account for the changes in the dissolved and particulate composition of seawater that strictly empirical algorithms cannot.

It may be argued that one emerging exception to the lack of in situ biogeochemical sensing technology 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
Twardowski, Lewis, Barnard, and Zaneveld
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.

Table 1. Some biogeochemical properties derived from optical properties.

<table>
<thead>
<tr>
<th>Biogeochemical property</th>
<th>Optical Property</th>
<th>Example Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate Organic Carbon (POC)</td>
<td>1) ( c_p ) or ( b_p )</td>
<td>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</td>
</tr>
<tr>
<td></td>
<td>2) ( b_{bp} )</td>
<td>Stramski et al. 1999; Balch et al. 1999</td>
</tr>
<tr>
<td>Total Suspended Matter (TSM)</td>
<td>1) ( c_p ) or ( b_p )</td>
<td>Peterson 1978; Gardner et al. 1993, 2001; Walsh et al. 1995; Prahl et al. 1997</td>
</tr>
<tr>
<td></td>
<td>2) turbidity</td>
<td>Fugate and Friedrichs 2002</td>
</tr>
<tr>
<td>Dissolved Organic Matter or Carbon (DOM, DOC)</td>
<td>1) ( a_g )</td>
<td>Pages and Gadel 1990; Vodacek et al. 1997</td>
</tr>
<tr>
<td></td>
<td>2) Fluorescence</td>
<td>Coble et al. 1993; Ferrari et al. 1996; Klinkhammer et al. 2000</td>
</tr>
<tr>
<td>DOM composition*</td>
<td>1) ( a_{q} ) spectral shape</td>
<td>Carder et al. 1989; Blough and Green 1995</td>
</tr>
<tr>
<td></td>
<td>2) Fluorescence, multi-spectral shapes</td>
<td>Coble 1996; Del Castillo et al., 1999; McKnight et al. 2001</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>1) ( a_p )</td>
<td>Bricaud et al. 1998; Claustre et al. 2000</td>
</tr>
<tr>
<td></td>
<td>2) Fluorescence</td>
<td>e.g., Yentsch and Menzel 1963; Claustre et al. 1999</td>
</tr>
<tr>
<td>Phycobiliproteins</td>
<td>Fluorescence</td>
<td>Cowles et al. 1993; Sosik et al. 2002</td>
</tr>
<tr>
<td>Phytoplankton pigment ratios</td>
<td>( a_p ) spectral shape</td>
<td>Trees et al. 2000; Eisner et al. 2003</td>
</tr>
<tr>
<td>Proteins</td>
<td>Fluorescence</td>
<td>Coble et al. 1993; Mayer et al. 1999</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>Fluorescence</td>
<td>e.g., Holdway et al. 2000</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>1) ( c_p ) spectral shape</td>
<td>Morel 1973; Boss et al. 2001</td>
</tr>
<tr>
<td></td>
<td>2) ( \beta(0) )</td>
<td>Brown and Gordon 1974; Zaneveld et al. 1974; Agrawal and Pottsmith 2000</td>
</tr>
<tr>
<td>Particulate refractive index</td>
<td>1) ( \beta(0) )</td>
<td>Brown and Gordon 1974; Zaneveld et al. 1974</td>
</tr>
<tr>
<td></td>
<td>2) ( c_p(\lambda), b_{bp}, ) and ( b_p )</td>
<td>Twardowski et al. 2001</td>
</tr>
<tr>
<td>Sewage</td>
<td>Fluorescence</td>
<td>Petrenko et al. 1997</td>
</tr>
<tr>
<td>Nitrate</td>
<td>UV absorption</td>
<td>Johnson and Coletti 2002</td>
</tr>
</tbody>
</table>

*For example – ratio of dissolved humic acid to fulvic acid, DOM molecular size distribution, DOM aromaticity, DOM source
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-

![Figure 3](image)

**Figure 3.** (A) A vertical profiling system during deployment; (B) a vertical profiler in preparation for work in the field. The picture in (B) shows a configuration for simultaneously measuring dissolved and particulate $a$ and $c$ components of seawater (note capsule filter attached to intakes of meter on the left).
time viewing at the surface. Ballast is often added to a profiler to bring the net weight underwater near neutral (see white floats in Fig. 3A). This enables a slow, steady descent rate when free-falling in order to resolve vertical fine structure.

There are several 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. 2001) must be avoided if possible. AOP profiling systems consequently have been developed that allow for profiling tens of meters from a ship (Fig. 4). These profilers are also designed so that the radiance (down-looking) and irradiance (up-looking) sensors are oriented very close to vertical during profiling, so that $L_u$ in the nadir direction ($\theta = \pi$) is measured and only the downwelling photons are included in $E_d$.

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 relative to deployment on autonomous platforms 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 in the past) 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. One limitation is the relatively high cost. Another is the relatively restricted time-space domain covered with vertical profiling data from a typical cruise. Nonetheless, in the foreseeable future it is difficult to envision a sampling strategy for remote sensing algorithm development and/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, pers. comm., 1998) and via helicopter during the 1997-1998 European COASTTOOC (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 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
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 phytoplankton layer centered at ~28 m.

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 and 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 (B. de Young, Memorial University, St. Johns, Newfoundland, pers. comm., 2004).

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 promising results. This work demonstrates the concept of using arrays of platforms separated at the critical scales needed to resolve coastal biogeochemical phenomena.

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.

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 waves 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 deployment and recovery. Furthermore, the power requirements of these systems including winch are demanding (more than 100 W).

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 over a wide range of time scales, 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 subsurface 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, pers. comm., 2000) or for ferries or ships of opportunity (Schroeder and Petersen, 2000; Balch et al., in press). An important consideration in any flow-through system with optical sensors is the elimination of bubbles. Consequently, holding tanks or in-line debubblers are often employed.

Figure 6. Vertical profiling from a helicopter during the COAST/OOC campaign. Photo courtesy of M. Babin.
Optical data from flow-through systems effectively resolve small horizontal scales that stationary vertical profiling systems cannot (Pegau et al., 2000). Surface data are 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 analogue.

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. 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 continuously from the vehicle through a hose embedded in the tow cable to the boat.

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 AC9 sensor, and a CTD.
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 do 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).

![Figure 8](image)

**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.
While several moored systems for remote sensing applications 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 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 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). Coastal moorings are highly susceptible to biofouling, characterized by the build-up of detrital and living organic matter on optical sensing interfaces (Fig. 9). In order to ensure data integrity, optical sensors on coastal moorings must currently 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 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 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.gomoos.org). The primary purpose of the in situ bio-optical component of the Gulf of Maine Ocean Observing System (GoMOOS) mooring

![Figure 9](image.png)

**Figure 9.** Biofouling of optical sensors at GoMOOS after 5 months at sea. (A) before; (B) after (picture taken in 2002).
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 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 (Fig. 9A). 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, Webb Research, Corp, pers. comm., 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, Webb Research, Corp, pers. comm., 2003). Other cost-effective drifting profiling floats such as the Oceans Sensors, Inc. Autonomous Profiling Vehicle (APV) 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 over about a four month period, capturing the onset of the spring bloom and the accompanying subsurface stratification. Vertical attenuation coefficients, $K_d$, could be determined for each irradiance profile and showed excellent agreement with the SeaWiFS K490 product. This study demonstrates the potential of expanding the 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. POC was derived by a linear empirical relationship and the assumption was made that the composition of the particle population varied by only small amounts during the deployment. 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 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

Autonomous Underwater Vehicles (AUVs) provide their 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 dollars.

Battery power with AUVs is currently one of the key limiting factors in their long-term use. Most propelled AUVs are 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, SubChem, Inc., pers. comm., 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), and typically travel in a “sawtooth” pattern. Although traveling velocity in the horizontal is relatively slow (< 0.5 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. Figure 10A shows a deployment by the Rutgers University 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. Data from this sensor is shown in Fig. 11.

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).

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.
In-water Instrumentation and Platforms

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, Rutgers U. glider team.

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
Figure 11. Attenuation data from a glider deployed by the Rutgers glider team in (A) Buzzards Bay, MA, 8/19/2003, and (B) the west Florida coast, 11/06/2003.
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 determinations require laboratory analysis on discrete samples. Overcoming the necessity to collect discrete samples could substantially accelerate future algorithm development/validation efforts. Developing accurate in situ biogeochemical sensing technology compatible with automated remote operation should thus be a continued area of focus by the oceanographic community.

At the present, the problem of sampling strategy is (whether we accept it or not) at least constrained by several factors, including the availability of sensing technology, the availability of platform technology, and 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 programmatic 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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6. References

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