Instruments and methods

Spectral light absorption and attenuation measurements from a towed undulating vehicle

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Abstract

Measurements from a nine-wavelength light absorption and attenuation instrument mounted on a towed, undulating vehicle (SeaSoar) capable of rapidly profiling the water column – complete up-down cycles in 1.5–12 min depending on the maximum sampling depth – are used to characterize strong spatial variations in the distributions of upper-ocean bio-optical properties. Water sampled from adjacent to the conductivity and temperature sensors located in the nose of the vehicle is pumped through the 25-cm dual optical flow tubes of a Western Environmental Technology Laboratories (WET Labs) ac-9 instrument mounted on top of SeaSoar. A three-stage algorithm for post-processing the optical data to insure high-quality measurements concurrent with conductivity–temperature–depth data is described. After synchronizing the optical, navigational and conductivity–temperature–depth data streams, the method relies on finding the optimal time delay between when a water parcel is sampled first by the temperature and conductivity sensors and then by the absorption and attenuation optics. After applying the calculated time-dependent lag, a correction for the dependence of light absorption on temperature and salinity and a scattering correction to absorption are made. The final processed optical data from SeaSoar compare well with the same parameters sampled by a slowly lowered vertical profiling package deployed from a nearby stationary vessel. A 2-h, 30-km long cross-shelf section consisting of 184 vertical profiles separated by 150–200 m reveals strong horizontal variations on short spatial scales (1 km or less) of the vertical distributions of bio-optical properties. © 1999 Elsevier Science Ltd. All rights reserved.
1. Introduction

Near open-ocean fronts, and over the continental margin in general, variability in hydrographic, velocity and bio-optical fields exists on short spatial scales. Strong variations in the vertical are driven, for example, by air–sea interactions and boundary layer dynamics. In the horizontal, physical variability comes from wind- and buoyancy-driven flows (e.g., Ekman convergence and divergence and the resultant fronts; freshwater sources near the coast) and from intrinsic hydrodynamic instability of energetic, sheared flows. Bio-optical variability in the horizontal is often linked with physical variability (e.g., Denman and Gargett, 1983) but can also be driven by biological and/or photochemical (e.g., Mopper et al., 1991) processes.

In addition to strong spatial variability, flows over the continental margin and mesoscale variations (eddies and meanders with scales of order the internal Rossby radius of deformation) associated with open-ocean fronts are characterized by short temporal scales. On time scales less than a season, physical variability includes wind driving on 2–5 day time scales, intrinsic flow variability forced, for example, by flow instability with one to a few days time scale, and diurnal changes in the upper ocean. Bio-optical fields are affected by flow fields with these same time scales, by diurnal changes in photosynthetically available radiation (e.g., Stramski and Morel, 1990), as well as by grazing and production (e.g., Cullen, 1982; Cullen and Lewis, 1995) and photodegradation (Vodacek et al., 1997) on time scales of order a few days to a week.

To accurately map the three-dimensional structure of these physical and biological fields, a method is needed to rapidly sample the water column over an extended horizontal region. Rapid sampling implies fast horizontal tow speeds and fast excursions in the vertical, thus necessitating instruments capable of high-frequency sampling. Towed, undulating measurement platforms are ideal for this purpose and have been used to measure both vertical and horizontal variability. One type of such an instrument uses moveable wings to control depth while being towed in excess of 6 knots (3.1 m s\(^{-1}\)). Examples of these towed, undulating instrument packages include Batfish (Dessureault, 1976) and SeaSoar (Pollard, 1986). These vehicles are large enough to carry substantial instrument payloads typically consisting of a rapid-sampling conductivity–temperature–depth (CTD) instrument and a variety of other physical and bio-optical sensors. Examples of the latter category are single-wavelength fluorometers, single-channel transmissometers and solar irradiance sensors. An example of a more complex bio-optical sensor is an optical plankton counter (Hermann, 1988), which has been flown aboard both Batfish (Hermann, 1988) and SeaSoar (Huntley et al., 1995).

Only recently has it become possible to use multi-wavelength optical measurements to investigate the patterns of bio-optical components and processes. For example, a three-wavelength fluorometer has been flown on SeaSoar and used to investigate the distributions of phytoplankton assemblages (Cowles et al., 1994). Many investigators have used multi-wavelength absorption and attenuation instruments (Moore et al., 1992) on both vertical profiling packages (e.g., Zaneveld et al., 1994) and on moorings (e.g., Dickey et al., 1998). Information on phytoplankton, particulates and dissolved
organic matter can be derived from spectra of light absorption and attenuation (Prieur and Sathyendranath, 1981).

In this paper we describe the use of a nine-wavelength absorption and attenuation instrument (ac-9, Moore et al., 1992) manufactured by Western Environmental Technology Laboratories Inc. (WET Labs) on the towed, undulating vehicle SeaSoar to obtain rapid, high-resolution, three-dimensional maps of bio-optical variability in the upper ocean. In the next section, the ac-9 and SeaSoar instruments and their integration are described. In section three, the data processing techniques required to produce reliable optical measurements concurrent with CTD observations from SeaSoar are detailed. In Section 4, results obtained during the Office of Naval Research sponsored Coastal Mixing and Optics (CMO) experiment conducted in 1996–1997 on the continental shelf south of Cape Cod, Massachusetts, are presented. The final section contains a brief summary and discussion. The intent here is to describe the multi-wavelength sensing system and to demonstrate its ability to define bio-optical variability. One example of using this system to discern physical circulation processes that influence bio-optical property distributions is found in Barth et al. (1998), and a more complete description of the three-dimensional structure of the physical oceanographic and bio-optical fields in the CMO region is forthcoming.

2. ac-9 on SeaSoar

A 25-cm pathlength, nine-wavelength absorption and attenuation instrument (ac-9) was mounted on the top of the towed, undulating vehicle SeaSoar (Figs. 1 and 2). The ac-9 measures light absorption (“a”) and attenuation (“c”) at each of nine wavelengths (Table 1) at 6 Hz. The ac-9 was also equipped with a pressure sensor. A conducting tow cable carries power to and data from the onboard instruments, as well as transmitting signals to control the vehicle’s flight pattern. The ac-9 was mounted outside the vehicle body because the interior space was occupied by: a Sea-Bird Electronics (SBE) 911 + CTD, including a pressure housing containing electronics, dual temperature/conductivity (T/C) sensors mounted in the nose of SeaSoar pointing forward (Fig. 2, bottom) and dual pumps for pumping water through the T/C sensors; a hydraulic unit to move the vehicle’s wings; and an optional power and data communications module (Fig. 1). The ac-9 was mounted on top because experience showed that adding weight to the vehicle had less effect on the flight characteristics if mounted there. A streamlined cap was added to the forward end of the ac-9 (Figs. 1 and 2) to avoid presenting the instrument’s flat endcap to the oncoming flow. The net result was no adverse effect on the vehicle’s flight characteristics. The ac-9 was mounted horizontally in a rigid saddle with supports both fore and aft (Fig. 2, top). The rigid saddle was designed to avoid placing torque on the light paths through the ac-9’s flow tubes (WET Labs, 1995; Moore et al., 1997).

Water was supplied to the ac-9 flow tubes by a SBE 5T 3000-rpm centrifugal pump capable of an unrestricted flow rate of 150 ml s⁻¹. The pump was mounted to the ac-9 frame (Figs. 1 and 2) and was located downstream in the flow, which entered at an inlet just above the CTD T/C sensors to ensure comparable CTD and optical
measurements, flowed through a 1/2"-ID hose to the ac-9 “a” flow tube, then entered the “c” flow tube before passing through the pump and being exhausted through a 1/2"-ID hose with its outlet located near the inlet in the nose of SeaSoar (Fig. 2). The outlet was located at the same level as the inlet to avoid placing a hydrostatic pressure gradient on the optical flow path, and was located symmetrically, with respect to the flow around SeaSoar, from the inlet to minimize any dynamic pressure gradient. The actual flow rate realized through this system is reported in the next section.

The ac-9 operates with 10−18 V, requires 9 W of power and sends data at about 400 bytes s⁻¹ over a RS-485 serial channel (WET Labs, 1995). These requirements can be supplied by a power and data communications package, for example a WET Labs Modular Ocean Data and Power System (MODAPS) or by running off a fast serial channel (9600 baud) from a SBE 911+ CTD. Both configurations have been used successfully, but the results presented here from the CMO experiment were obtained by using MODAPS. Data are received and stored on shipboard PCs or Unix workstations. The serial data stream is also input to a realtime monitor and display software package (Fig. 3), which allows the user to monitor the instrument’s performance. This is critical for successful operation of an ac-9 aboard SeaSoar for immediate detection of clogging of the flow tubes, faulty pump operation or a flow tube being jarred loose. Throughout the 11 days of towing SeaSoar during the 1996 CMO experiment, it was only necessary to recover the vehicle a few times to correct a
Fig. 2. (top) Closeup of the spectral absorption and attenuation meter (WET Labs ac-9) mounted on top of SeaSoar showing pump and hose configuration. (bottom) Inlet and outlet for the ac-9 water supply located in SeaSoar's nose adjacent to the dual Sea-Bird temperature-conductivity sensors.

Table 1

<table>
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<th>λ (nm)</th>
<th>412</th>
<th>440</th>
<th>488</th>
<th>510</th>
<th>532</th>
<th>560</th>
<th>650</th>
<th>676</th>
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<td>0.04</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>c (m(^{-1}))</td>
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<td>0.07</td>
<td>0.08</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Problem with the optics. The monitor displays "a" and "c" spectra (Fig. 3, upper right) as the vehicle transits through the water column. The display system also allows single channels or algebraic combinations of channels to be displayed as time series (Fig. 3, lower right) or as color raster plots in a time-depth orientation (not shown). By plotting bio-optical properties of the water column (e.g., absorption by phytoplankton) in realtime and with fine spatial resolution, targeted sampling concentrated on bio-optical features (e.g., subsurface absorption maxima; patchiness associated with fronts and eddies) can be performed.
An important consideration for processing and analyzing data from SeaSoar is its flight pattern through the water column. The vehicle samples from the surface to within 5–10 m of the bottom – the ship’s echosounder is used to detect the bottom and is supplied to the SeaSoar control software to avoid bottom collisions – while being towed at 6–8 knots (3.1–4.1 m s\(^{-1}\)) behind a research vessel. During the CMO experiment conducted over the continental shelf, the time to complete an up-down cycle varied between 1.5 and 4 min for shallow (55 m) and deep (105 m) profiles, respectively. The vehicle’s vertical speed varies with depth and differs between the ascending and descending profiles (Fig. 4). Vertical speeds range from 0–3 m s\(^{-1}\) with a typical value of 1 m s\(^{-1}\), which we note is in excess of the typical descent and ascent rates used while profiling from a stationary research vessel. The variable flow past the vehicle may also influence the pumped flow rates through dynamic pressure gradients, although as demonstrated in Barth et al. (1996) this effect is small. The vehicle’s
vertical velocity influences the ac-9’s vertical resolution given its 6-Hz sampling rate and is critical for calculating depth offsets from time lags induced by water samples passing through the plumbing and optical flow tubes.

3. Data processing

The ac-9 data processing is illustrated here using a selected cross-shelf transect from the 1996 CMO experiment. We have selected this particular section (2600 s long) because it is located close to and is concurrent with bio-optical measurements made from a stationary research vessel also participating in the CMO experiment (Pegau et al., 1998). To obtain meaningful data from the towed ac-9, various correction and calibration procedures have to be performed. A major goal of this processing is to use the CTD data to provide a measure of the temperature and salinity of the optical sample so that the optical data can be corrected for dependence on these properties. Our effort to align two independent data streams so that important corrections to one that are dependent on the other can be made is analogous to the careful processing of
temperature and conductivity signals from a CTD that must be done to ensure quality salinity data (e.g., Lueck, 1990; Lueck and Picklo, 1990; Morrison et al., 1994).

The zeroth stage of processing involves instrument calibration and is carried out using the factory-provided DOS-based software (WET Labs, 1995). The software reads in the raw binary 6-Hz ac-9 data, converts “a” and “c” signals and reference values to uncorrected inverse meters, applies a linear correction dependent on the internal temperature of the instrument and applies wavelength-dependent clean water offsets derived from a pre-cruise factory calibration to obtain corrected “a” and “c” values in inverse meters (WET Labs, 1995).

Next, the 6-Hz ac-9 data stream is averaged to 1-s values then merged with the ship’s GPS navigational record as well as with the SeaSoar CTD data stream (pressure, temperature, salinity and density). The ac-9 data stream, although recorded concurrently in real-time with the rest of the data, must be processed to account for delays in the transmission of data packets, flow delays due to residence time in the plumbing, and random errors due to sometimes poor transmission. The main purpose of our data processing is to remove these effects. At stage I of our processing, we synchronize the ac-9 data stream with the rest of the SeaSoar data by matching the two independent pressure traces. Since we know the depth of the ac-9 at the internal time of the ac-9 and we also know the depth and the real world time from the CTD and GPS, respectively, overlapping the two pressure traces allows us to provide a time and location stamp for the ac-9 data stream. This process has led to the discovery that the ac-9 acquisition system clock drifts on average 1 s over 1000 s, and the drift varies considerably with time.

This data stream is the input for the next level of processing. While the SeaSoar is moving rapidly through the water column, 3.1–4.1 m s\(^{-1}\) in the horizontal and 0–3 m s\(^{-1}\) in the vertical (see Fig. 4), the ac-9 records values of absorption and attenuation at 6 Hz. This rapid movement through the water column is in sharp contrast to the typical ac-9 vertical profiling operation (WET Labs, 1995), where the ac-9 is usually lowered at a speed of 0.5 m s\(^{-1}\) or less. As the SeaSoar traverses the water column, the ac-9 samples water with a flow rate that depends on the details of the ac-9 plumbing system, the ac-9 pump setup and, possibly, the characteristics of the flow around the SeaSoar body in the vicinity of the ac-9 plumbing inlet/outlet. Since it takes a finite time for the water sample to transit from the plumbing inlet/outlet to the optical tubes, a delay, which may be time-dependent, is introduced between when the pressure of the sample is recorded, as measured at the depth of the ac-9 instrument, and when the optical measurements are made. This results in a depth offset between optical measurements made on the descending profile versus those made on the ascending profile, as well as with their true depth (Fig. 5a) (we will use pressure and depth interchangeably in the discussion to follow, a good approximation in the upper ocean). We note that these plumbing related, space- and time-variable, and a priori unknown delays introduced during the SeaSoar acquisition go far beyond the constant and known delays associated with the vertical profiling mode of ac-9 data acquisition.

Stage II of the processing algorithm finds an optimal time lag by varying the applied lag to minimize the difference between the descending and ascending profiles.
This technique relies on the existence of vertical variations in optical properties over the water column, a common situation in the coastal ocean where subsurface light-absorbing and light-attenuating phytoplankton layers and light-attenuating bottom resuspended sediment layers often exist (e.g., Fig. 5a). Furthermore, it is assumed that the optical properties are horizontally uniform over the distance between SeaSoar ascending and descending profiles. During the CMO experiment conducted over the continental shelf, this distance at the top and bottom of the profile varied between 300 and 800 m for shallow (55 m) and deep (105 m) profiles, respectively. Given the sawtooth shape of the SeaSoar flight path, at other depths the horizontal separation is reduced, e.g. by a factor of two at mid-depth so that measurements are separated by 150–400 m depending on the profiling depth.

To find the optimal time lag, the 1-s ac-9 measurements are first linearly interpolated to a finer spatial grid with 200 points in the vertical, so a typical profile has a grid spacing of 100 m/200 = 0.5 m. To translate between time lags and depth offsets, the vertical velocity $w$ (Fig. 4) of the vehicle is computed from time-differencing the CTD pressure record then filtering with a five-point running mean. For a vertical velocity
of 1 m s\(^{-1}\) the five point filter is about 2 s wide. Next, the time lag in the relation \(z(\text{true}) = z(\text{measured}) - w \cdot \text{lag}\) is varied to minimize (in the least-squares sense) the difference between the measured optical signal on the ascending and descending traces. The optimum lag is calculated for each of the nine wavelengths of both “a” and “c” because the 18 channels are not measured simultaneously.

For the example 2600-s transect our method found 26 lag values at each of eighteen “a” and “c” channels. The average delay over nine wavelengths for “a” and “c” are shown separately in Fig. 6. The mean delay over all 26 pairs for “c” is approximately 1.35 s and that for “a” is \(-0.15\) s. The negative value exists because these delays are a sum of the same (for both channels) unknown negative delay (due to ac9 acquisition software in which pressure is recorded at the end of each data packet) and the “physical” delay due to a finite rate of fluid flow carrying a water sample to each ac9 detector over a finite tubing length. The difference between the observed “a” and “c” delays gives a total delay of 1.5 s. Knowing the length and inner diameter of the tubing we estimate that the flow speed (inversely \(\propto\) delay difference of “a” and “c”) was fairly constant at around 50 ml s\(^{-1}\), in good agreement with the 46 ml s\(^{-1}\) reported for a Sea-Bird 5T operating at 3000 rpm to pump water through a Sea-Bird conductivity

![Fig. 6. Time delays from lagged correlation of adjacent up and down optical profiles as a function of up-down profile pair along the SeaSoar track.](image-url)
cell (Sea-Bird Electronics SBE 5T specification sheet). Here we also observe that the variance of the difference between the “a” and “c” lags (open circles and solid thick curve in Fig. 6) is smaller than the variance for either the “a” or “c” lags alone, an indication that we are obtaining a good estimate of the physical delay.

For each “a” and “c” channel, the optimum time lag is then multiplied by the depth-dependent vertical velocity to obtain the true depth of the optical measurements. An example of a vertical profile of “c” at 532 nm before and after removing the delay is shown in Fig. 5.

To find the relative “error” of the ac-9 measurements we plot the difference between the ascending and descending absorption measurements at 532 nm normalized by the descending values as a function of depth for the entire 2600-s transect (Fig. 7a). These
differences could be due to both the processing technique, e.g. inability to get a good least-squares fit between ascending and descending profiles, and natural horizontal variability between profiles (see discussion of Fig. 11 in Section 4). We also plot the difference in vertical speed of the SeaSoar vehicle between the ascending and descending profiles (Fig. 7b). The relative “error” is less than 10% for all “a” and “c” channels, and there is no visible dependence in the “error” on vertical speed, lending confidence to our processing algorithm. The lag-corrected “a” and “c” profiles at the nine wavelengths serve as input to stage III, the final stage of processing.

At stage III we apply a correction for the dependence of absorption on temperature and salinity, largest in the near infrared (715 nm), using the technique of Pegau and Zaneveld (1994) and Pegau et al. (1997). Unfortunately, the ac-9 does not measure the temperature – the temperature effect being much larger than the effect due to salinity – of the ambient water, so we use the lag-corrected temperature as measured by the CTD sensor located in the nose of SeaSoar. For our cruise, the variations in the salinity correction are small enough to warrant the use of a constant salinity for this correction (Moore et al., 1997). Next, a correction is made for the fact that reflecting tube absorption meters, as used in the ac-9, do not collect all of the light scattered from the beam and thus overestimate the absorption coefficient. We use the technique recommended by the manufacturer when measurements of “a”, “c” and temperature are all available (WET Labs, 1995; Moore et al., 1997). Following Zaneveld et al. (1994), the technique uses a reference wavelength to determine the proportion of the scattering coefficient to be subtracted from the absorption signal. Note that reported absorption values do not include the wavelength-dependent absorption due to water.

Since frequent cleaning and calibration of the ac-9 mounted aboard SeaSoar are not possible due to the multi-day tows, a final wavelength-dependent offset is obtained by comparing our data to values measured by a concurrent nearby vertical optical profiling instrument operated by the Oregon State University optics group on board a stationary research vessel (Pegau et al., 1998). In the absence of another optical data set with which to compare, reliable light absorption and attenuation data may be obtained through the use of pre- and post-tow calibrations of the ac-9 using air or, preferably, optically clean water as recommended by the manufacturer (Moore et al., 1997).

4. Results

A set of SeaSoar profiles from the mid-shelf (40.5°N, 70.5°W, 70-m isobath) south of Cape Cod, Massachusetts, in the Middle Atlantic Bight reveals the physical and bio-optical structure of the water column (Fig. 8). A warm, fresh upper layer is separated from cold, salty water below by a strong pycnocline located around 15–25 m depth. A salty intrusion lies within the pycnocline, and cold, salty water is found near the bottom (z > 52 m). The upper part of the water column (0–15 m) has relatively low light attenuation and absorption. Subsurface maxima in absorption and attenuation at 532 nm are centered near 27 m in the lower part of and just beneath the strong pycnocline. These peaks correspond to a deep chlorophyll maximum that in
a previous study in the same geographic region during the same month was ascribed to phytoplankton exploiting high nutrients and sufficient light at this depth (Houghton and Marra, 1983). Both “a” and “c” at 532 nm increase again near the bottom, indicative of material associated with the bottom boundary layer. Horizontal variability in the vertical distribution of physical and bio-optical properties is indicated by differences between the multiple profiles: five for SeaSoar CTD data and eight for SeaSoar ac-9 data (Fig. 8). The bold line in each panel indicates the SeaSoar profile closest to 40.5°N, 70.5°W, the location of optical vertical profiles made from the stationary R/V Seward Johnson (Pegau et al., 1998).
Fig. 9. Comparison of SeaSoar and stationary ship vertical profiler (thin solid curves) ac-9 data as a function of depth. SeaSoar ac-9 data is shown both for processed (dashed curves) and corrected (thick solid curves) data from the ascending and descending profiles closest to the stationary ship data.

A comparison of stationary ship and SeaSoar ac-9 measurements is shown for “a” and “c” at 532 nm (Fig. 9). The SeaSoar profile was made one-half hour earlier and 0.6 km away from the stationary ship measurements. Data are shown for the upper 40 m, excluding the more highly variable, both in space and time, signal near the bottom boundary layer. The shipboard ac-9 profiles have more samples in the vertical both because the instrument was being lowered slowly (~0.20 m s⁻¹) and because the full 6-Hz data are plotted. The shipboard and SeaSoar profiles are very similar in shape but are offset. The differences in peak amplitudes can readily be explained by horizontal variability in the strength of the subsurface chlorophyll maximum (Fig. 8; Fig. 11 and discussion below). A similar situation is found for other wavelengths. We find the wavelength-dependent offsets by demanding that the mean shipboard and SeaSoar spectra should be as close as possible for water between 0 and 20 m depth. The extent of the water column used for this calculation is somewhat arbitrary, and the only true requirement is that it be the part of the water column with small spatial and temporal variability. That this is true for the upper 20 m is apparent from the
optical profiles shown in Fig. 8 and will also be evident in data presented for an entire cross-shelf section (see discussion regarding Fig. 11 below). This procedure yields a systematic wavelength-dependent offset to both “a” and “c” between the SeaSoar ac-9 data and stationary slow-drop vertical profiling ac-9 (Table 1). This offset was applied to the final data set, and the results for one spectral component are shown in Fig. 9.

A comparison of “a” and “c” spectra using an average of the upper 20 m of the water column from both the SeaSoar ac-9 and stationary ship ac-9 is shown in Fig. 10. The spectra of absorption are virtually the same for the SeaSoar and the ship data with similar variances. Note the small variance for SeaSoar ac-9 \( a(715 \text{ nm}) \) where the temperature correction for absorption is largest. The success of the SeaSoar ac-9 data processing described in Section 3 is verified by the comparable variances of SeaSoar and stationary ship observations at \( a(715 \text{ nm}) \) (Fig. 10). The “c” spectra are very similar as well, but here SeaSoar variances are somewhat smaller than that of stationary ship data. From this comparison we conclude that the towed, undulating
optical measurements after processing and calibration, and after appropriate vertical averaging, are of the same quality as their slowly lowered, stationary vessel counterparts.

The real power of using a multi-wavelength optical instrument onboard a towed, undulating vehicle capable of sampling rapidly with high spatial resolution is revealed by a 30 km long cross-shelf section consisting of 184 profiles obtained in just over two hours over the continental shelf south of Cape Cod, Massachusetts (Fig. 11). The vertical sections of temperature and salinity show the same basic vertical structure as revealed by the individual profiles (Fig. 8), but significant horizontal variability in these properties exists across the shelf. Fresh surface layer water is found inshore while salty water is found offshore at depth, the latter indicative of the influence of continental slope water farther offshore (Beardsley et al., 1985). Spatial variability in the
pycnocline across the shelf also exists, with a general upward slope in the isopycnals offshore (south) of 40.55°N associated with a mean alongshore geostrophic flow to the west typical of this shelf region (Beardsley et al., 1985).

Chlorophyll absorption, an indicator of chlorophyll concentration, is obtained by computing the area under the 676-nm peak above the background absorption level: \( a_{676} = (a_{650} + a_{715})/2 \) (Fig. 11). The depth of the core of the subsurface chlorophyll maximum varies considerably across the section, generally tracking the depth of the lower part of the pycnocline. Differences in the strength along the core of the chlorophyll maximum are readily apparent. Significant differences in the vertical gradients both above and below the chlorophyll subsurface maximum are also present (cf., near 40.45 and 40.55°N). There is virtually no chlorophyll absorption near the bottom.

Light attenuation at 650 nm tracks chlorophyll absorption in the subsurface phytoplankton maximum (Fig. 11). High light attenuation is also found near the bottom on the inshore half of the cross-shelf section, due to suspended bottom material which does not absorb light in the 676-nm chlorophyll band. Differences in \( c_{650} \) amplitude along the bottom are also apparent and may reflect variations in the physical processes responsible for resuspension found there (e.g., Smith, 1977; Bogucki et al., 1997). There also exist sharp subsurface fronts (widths of 1 km or less) in optical properties in both chlorophyll absorption (e.g., near 40.475°N, 30–50 m depth) and light attenuation at 650 nm (e.g., near the bottom at 40.5°N), which are well-resolved by the rapidly profiling SeaSoar system.

Finally, we note that vertical profiles of physical and optical properties at a single shelf location (e.g., near 40.5°N, 70.5°W, the location of a stationary ship during the CMO experiment) can be greatly aided by the rapid measurement of spatial variability possible using CTD and multi-wavelength optical instruments aboard a towed, undulating vehicle.

5. Summary and discussion

A multi-wavelength light absorption and attenuation instrument has been used successfully from a towed, undulating vehicle capable of rapidly profiling the water column. The nine-wavelength, 25-cm pathlength optical instrument (WET Labs ac-9) was mounted on top of SeaSoar and water, originating adjacent to the CTD temperature and conductivity sensors in the nose of SeaSoar, was pumped through the dual optical flow tubes. Optical data was monitored in realtime through the use of a windows-based software display package, which helped ensure a continuous stream of high-quality data and may be used for targeted sampling of bio-optical features (e.g., fronts, eddies).

After carrying out basic instrument calibration using factory-supplied software, a three-stage processing algorithm is applied. First, the ac-9 data stream is synchronized with the GPS navigational record and with the CTD data stream. Second, the optimal time delay between when the CTD measures a water sample and when that sample passes through the optical detectors is found to assign the correct pressure to
the optical data and to allow temperature-dependent corrections to be applied. This delay is time-dependent and is found at all nine wavelengths for both the absorption and attenuation channels by varying the applied lag to minimize the difference between adjacent descending and ascending optical profiles. The calculated lag is then multiplied by the time-dependent vertical velocity of the SeaSoar vehicle to calculate the depth offset. Third, corrections are made for the dependence of light absorption on temperature and salinity, and for the fact that reflecting tube absorption meters do not collect all the scattered light and thus overestimate the absorption coefficient. Lastly, since SeaSoar tows are often several days long and frequent cleaning and calibration of the ac-9 mounted on top are not possible, a wavelength-dependent offset is applied to the SeaSoar ac-9 data set through comparison with concurrent slowly dropped optical vertical profile data obtained from a nearby stationary ship. The final SeaSoar ac-9 data set is of high quality with spectral estimates having an average relative error of less than 1% compared with the stationary ship ac-9 vertical profile data (Fig. 10).

The algorithm presented here is optimal in the sense of finding best-fit lags for each of the eighteen “a” and “c” channels. This optimal least-squares solution is computationally intensive, but allows for the fact that each “a” and “c” channel may “see” the vertical structure of the water column differently as dictated by the distribution of optically active material. For example, near the bottom boundary layer inorganic re-suspended sediment will attenuate light but not affect light absorption in the chlorophyll band (e.g., Fig. 11). Although we explored the use of time lags based on either the mean delay over all nine “a” channels or the mean over all nine “c” channels with relatively good results, we chose to use the optimal processing algorithm.

By making rapid, high-spatial resolution sections, details of the subsurface optical properties can be discerned. These sections show strong horizontal variations on short spatial scales (1 km or less) of the vertical distributions of optical properties, e.g. chlorophyll absorption and light attenuation by suspended material. The advantage of the multi-wavelength measurements is that by examining the total absorption spectrum, information on the spatial distributions of phytoplankton, particulate detritus and dissolved organics can be determined (Prieur and Sathyendranath, 1981). Here we present results based on using four of the available 18 channels of light absorption and attenuation (Fig. 11). A subsequent paper will employ light absorption spectra decomposition techniques, which rely on measurements at all nine wavelengths, to describe the bio-optical property distributions over the shelf in the CMO region. Repeated sections can help differentiate local time-dependent changes from those due to advective influences. A set of vertical sections arrayed in a grid can reveal details about the three-dimensional distribution of optical properties. Papers describing these three-dimensional aspects of the physical and bio-optical data collected from SeaSoar during the CMO experiment are forthcoming. Finally, high-resolution optical data can be used not only to learn about biological processes, but also to discern details of the physical dynamics that influence bio-optical property distributions. An example of the latter was the detection of secondary circulation (flow in a cross-front, vertical plane) associated with a shelfbreak front in the Middle Atlantic Bight by Barth et al. (1998).
While our rapid physical and bio-optical surveys involved the towed, undulating vehicle SeaSoar, the techniques described here for producing reliable multi-wavelength bio-optical measurements are equally valid for other towed systems (e.g., Guildline Instrument’s MiniBAT; Geological and Marine Instrumentation’s Scanfish; Chelsea Instrument’s Nu Shuttle and Aquashuttle) and autonomous underwater vehicles. These measurement platforms and bio-optical instruments of increasing capability (complexity) are being used ever more frequently. With proper care, they can be used to rapidly characterize three-dimensional physical and bio-optical property distributions.

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References


