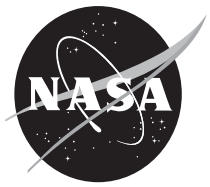
NASA/TM–2008–214157, Vol. 3



Wallops Coastal Ocean Observation Laboratory Project

Document Series, Volume 3

Absorption and Attenuation Coefficients Using the WET Labs ac-s in the Mid-Atlantic Bight: Field Measurements and Data Analysis

Nobuaki Ohi, Carla P. Makinen, Richard Mitchell, and Tiffany A. Moisan

April 2008

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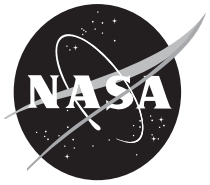

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Absorption and Attenuation Coefficients Using WET Labs ac-s in the Mid-Atlantic Bight: Field Measurements and Data Analysis

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Abstract

Ocean color algorithms are based on the parameterization of apparent optical properties as a function of inherent optical properties. The WET Labs underwater absorption and attenuation meters (ac-9 and ac-sac-s) measure both the spectral beam attenuation [c (λ)] and absorption coefficient [a (λ)]. The ac-s reports in a continuous range of 390-750 nm with a band pass of 4 nm, totaling approximately 83 distinct wavelengths, while the ac-9 reports at 9 wavelengths. We performed the ac-s field measurements at nine stations in the Mid-Atlantic Bight from water calibrations to data analysis. Onboard the ship, the ac-s was calibrated daily using Milli Q-water. Corrections for the *in situ* temperature and salinity effects on optical properties of water were applied. Corrections for incomplete recovery of the scattered light in the ac-s absorption tube were performed. The fine scale of spectral and vertical distributions of c (λ) and a (λ) were described from the ac-s. The significant relationships between a (674) and that of spectrophotometric analysis and chlorophyll a concentration of discrete water samples were observed.

The purpose of this report is to document calibration and data handling procedures used for the Wet Labs ac-s and ac-9 on the BIOME cruises, as well as software developed “in-house” to process and archive results.þ The documentation of these procedures and software is considered essential since considerable data has been collected on the BIOME cruises. This data is expected to be used in a variety of research efforts; some, of which, may not be directly related to the personnel involved in the BIOME sampling activity.

Acknowledgments

This work was supported by the NOAA Grant (NA03NOS4730220) under the auspices of the BIOME program. We thank NASA Headquarters for their attention to our work on the IOP rack.

We thank Dr. José L. Blanco for the earlier development of the IOP instrument package and assistance of WET Labs especially the WAP program, and Kristen L. Blattner and Matt Linkswiler for spectrophotometric and fluorometric analysis of discrete water samples. Our appreciation to Dr. Stanford Hooker for earlier criticisms which greatly improved our work. Dr. Michael S. Twardowski and Scott Freeman of WET Labs and Robert Swift of EG&G provided helpful comments on the manuscript. We also appreciate the hard work of the captain and crew of the RV *Hugh R. Sharp*. Thanks to the supporting agencies, especially Peter Jobse, Mark Yarosh, and Nancy Vorona of the Center for Innovative Technology.

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Section 1

Introduction

Ocean color algorithms are based on the parameterization of apparent optical properties (AOP), such as the diffuse attenuation coefficients for downwelling irradiance [K_d (Ψ)] and remote sensing reflectance (R_{rs}), as functions of inherent optical properties (IOP) and other factors such as chlorophyll (chl) *a* concentration. The K_d (Ψ) is related to the total absorption coefficient [a_t(Ψ)] as

1) K_d (Ψ) Ψa_t(Ψ)

where Ψis the wavelength. The R_{rs} is proportional to the ratio of backscattering [b_b (Ψ)] to a_t (Ψ) as (Gordon *et al*. 1975, Morel and Prieur 1977),

2) R_{rs} (Ψ) Ψ$G \cdot b_b$ (Ψ) / a_t(Ψ)

where *G* is a constant dependent on the angular distribution of the light field and the volume scattering coefficient. The spectral absorption coefficient is one of the inherent optically properties that influences the reflectance in aquatic systems. IOPs of water depends on the concentration and type of optically significant constituents. The total absorption [a_t (Ψ)] and scattering [b_t (Ψ)] coefficients can be described as,

3) a_t (Ψ) = a_w (Ψ) + a_{ph} (Ψ) + a_d (Ψ) + a_i (Ψ) + a_{CDOM} (Ψ)

4) b_t (Ψ) = b_w (Ψ) + b_{ph} (Ψ) + b_d (Ψ)

where subscripts w, ph, d, i and CDOM stand for pure water, phytoplankton, detritus, inorganic matter and colored dissolved organic matter, respectively. Scattering by CDOM is usually considered as negligible (Bricaud *et al*. 1981). The total attenuation coefficient corresponds to the sum of absorption and scattering coefficients as,

5) c_t (Ψ) = a_t (Ψ) + b_t (Ψ).

In recent decades, several researchers (e.g. Roesler 1998, Mitchell 1990, Mitchell *et al.* 2003) have developed laboratory spectrophotometric methods for measuring particle and detritical in absorption filtered water samples. Past studies have focused on the WET Labs *in situ* spectral *a* (Ψ) and *c* (Ψ) meter (ac-9) that have been deployed from ships (e.g. Sosik *et al.* 2001, Boss *et al.* 2004, Oubelkheir *et al.* 2005, 2006, Morel *et al.* 2006) and moored platforms (Chang & Dickey 2001) in support of ocean color satellite validation activities. However, the field measurements and data analysis using the ac-s have rarely been reported. The ac-9 and ac-s have dual, 25-cm path-length flow tubes and measure with a sampling rate of about 6Hz for both the spectral *c* (Ψ) in an enclosed flow-through non-reflective optical path, and the spectral *a* (Ψ) using parallel enclosed flow through reflective tube optical paths. The ac-9 reports nine wavelengths in the spectral range of 412 nm-715 nm with a band pass of 10 nm/channel while the ac-s reports in a continuous range of 390-750 nm with a band pass of 4 nm, totaling approximately eighty-three distinct wavelengths and is newest to the

scientific community. WET Labs, the manufacturer, provides detailed protocols for calibrating and using the instruments, and for analyzing their data, both in the ac-9 and ac-s User Manuals, and in a detailed protocol manual (Van Zee *et al.* 2005). Pegau *et al.* (2003) and Twardowski *et al.* (1999) have also indicated the field measurements and data analysis protocols for measuring the a ($\propto$) and c ($\propto$) using ac-9 and these are appended here. Also, we have knowledge of the method taught at the WET Labs official class.

We have been using the WET Labs ac-meters for projects since 2005 according to their protocols, and have continuously improved deployment and calibration methods, to a point where we now feel that the quality of data collected is somewhat comparable to laboratory methods for absorption measurements, such as spectrophotometry on the filter pad and with the integrating sphere (Kishino *et al.* 1985). We anticipate improvements in future cruises. This report documents the methods currently used for calibration and deployment of the ac meters, as of our most recent multi-day BIOME V cruise deployment from October 31 to November 2, 2006.

Section 2

Materials & Methods

2.1 Experiment Site

The Bio-physical Interactions in Ocean Margin Ecosystem (BIOME) V cruise was carried out in the Middle Atlantic Bight (Figure 2-1) aboard the R/V *Hugh R. Sharp*. The study area has a water depth from 15 m at Station 1 to ~ 800 m at Station 9. The data presented here was collected from October 31 to November 1, 2006. Vertical profiles of the ac-s and water-sampling casts were carried out.

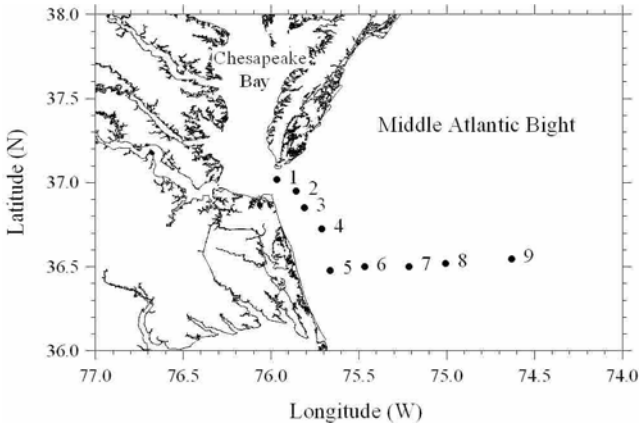

Figure 2-1 Location of the BIOME V cruise stations from October 31 to November 1, 2006

2.2 Instrument Rack Configuration

We currently operate an inherent optical properties (IOP) instrument package consisting of a CTD, fluorometer, backscatter meter, water pumps, and absorption meters. WET Labs absorption meters on the IOP package consist of an ac-9 and ac-spectra (ac-s). Both ac meters are configured into a data handler (WET Labs DH-4) with other instruments, including the CTD. The ac meters are positioned on the IOP frame in a vertical arrangement with inflow tubes at the bottom and outflow tubes at the top. A Sea-Bird Electronics pump (Model 5T) is connected to the outflow tubes of each ac-meter to draw water up through the flow tubes. At the intake of the ac meters, a sieve is attached to tygon tubing to prevent larger organisms from entering flow tubes and the tygon tubing is wrapped in black electrical tape to prevent extraneous light from entering the flow tubes and interfering with signals. Tygon tubing on the outflow ends of the meters is also wrapped in black electrical tape to exclude extraneous light from entering flow tubes at the tops of the ac meters. A capsule filter is sometimes attached between the sieve and absorption flow tube on the ac-9 when measuring CDOM absorption. A figure of the ac meter configuration with pumps and tubing on the IOP rack is shown in Figure 2-2.

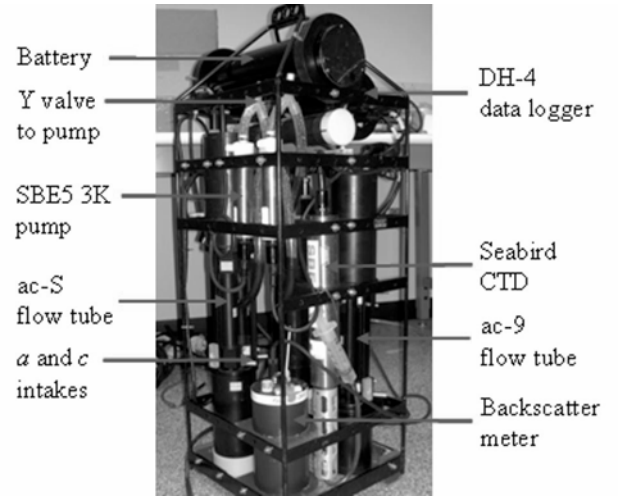

Figure 2-2 IOP Instrument Package

2.3 Deployment/Retrieval

The IOP rack is typically deployed at all oceanographic research stations to create profiles of various optical properties from approximately two meters below the sea surface to two meters off the sea floor. For a typical deployment, the rack is attached to a hydraulic winch with a shackle. The data handler is turned on just before deployment to prevent the pumps from taking in air, and the rack is lowered until all units are just below the sea surface. At this point, the rack equilibrates for a minimum of two minutes and visual checks are done; bubbles can be seen exiting from pumps and illuminated LEDs are visible on some instruments, indicating successful power supply to the instruments. After the two minute equilibration period, the package is released with a descent rate of 222-693 cm/sec to approximately two meters off the sea floor. This instrument package does not include a sea cable for real-time data viewing, and therefore, we cannot determine real-time instrument depth during casts. Winch operators typically let out just enough cable to estimate the package's position as being just above the sea floor. The package is then brought back to the surface with the same ascent rate as the decent rate. Upon retrieval of the IOP rack, power is removed from all instruments until the next deployment and the instruments are rinsed with fresh water.

2.4 Ship-board Calibrations

At the end of daily sampling activities during oceanographic research cruises, all ac meters are cleaned and then calibrated with a source of Milli-Q water which is close to optically pure water. (Pure water is produced on large research vessels with commercial systems.) Sieves and capsule filters are removed during the calibration process. Each flow tube is removed and cleaned, using Kimwipes, with 20% ethanol to remove dirt, grease, and other substances from the insides of flow tubes as well as the

detector windows. Optically pure water is then used to rinse cleaning chemicals from the ac meters.

The ac meters are then either attached directly to the pure water filtration systems to pump water through each flow tube, or to the spigot of a carboy filled with water stored for approximately four hours to debubble. When connecting directly to filtration systems, the tubing is attached to the intake of flow tubes and the water flow is initialized. The entire instrument rack is tilted all directions and lightly jostled to dislodge any air bubbles from flow tubes or detector windows. Once the air bubbles are removed and the water flow is equalized to prevent formation of new bubbles in flow tubes, WET View software is initialized for the specific instrument. Any bubbles remaining are typically apparent in the data displayed and calibrations are repeated until the data consistently shows low values for absorption ("*a*" tube) and attenuation ("*c*" tube), indicating a clean, stable instrument. The water temperature of calibration water is also recorded and used in later calculations, as water temperature can affect the instrument values.

2.5 Data Download

As previously mentioned, data from the ac meters is logged in an attached WET Labs DH-4. Upon completion of cruise activities, the instrument rack is plugged in for power charging and data is downloaded. WET Labs software indicates the files available on the DH-4, and select files are then downloaded for processing. Once downloading is complete, the DH-4 memory is cleared in preparation for future use. Downloaded files can be corrected and processed through the WET Labs Archive Processing (WAP) program or other user-specific command-line C programs.

2.6 User-Specific C Program Processing DH-4

The data from the DH-4 is decoded using an in-house program, dh4decode, a command-line C program developed in-house that dupl?cates how we were using the WET Labs WAP program. The decision to go this route instead of using WAP was based on our need to automate the daily data processing from buoys and have this automatically posted to the web. Most of our systems are Unix based and converting this to a program that runs on those systems simplifies the workflow.

WET Labs manuals on the DH-4, ac-9, and ac-s were used to determine how to read the binary data files from the DH-4 and provide the same corrections WAP applies when extracting the data. The final values are written to separate files for each sensor. A copy of the configuration files used is also written to separate files to document how the data was processed (see Descriptions).

2.7 Data Analysis

The profiling package consisted of a WET Labs DH-4 and Power Systems, Seabird CTD and 3000 rpm submersible pump with ac-s. A WET Labs DH-4 and Power System were used to power the instruments, acquire data, time stamp the data, and

transmit the data to PC. A Seabird 3000 rpm submersible pump was placed after ac-9 flow cells. Time lags were applied to profile data from the absorption meters to account for the time required for a water parcel to enter the intake tube and travel to the flow cell. The total volume of a flow cell was about 30 ml. Twardowski *et al.* (1999) reported the flow rate of the Seabird 3000 rpm submersible pump placed after the exiting "Y" of the ac-9 flow cells was about 25 ml s^{-1}, so the time lag was estimated around 1.2 s. Multiple profiles were acquired during deployment, and a single up-cast was selected (lower bubble). Time lags were applied to each profile to match the up-cast. Data from the ac-s and CTD were merged using software of WET Labs WAP Version 4.17.

The original ac-s pure water offsets are determined from water calibrations performed at WET Labs. These water offsets are contained in an instrument-specific [.dev] file that WETView applies by subtraction to all *in situ* measurements. Onboard the ship, calibration values by ac-s were obtained daily by averaging absorption and attenuation coefficients using water generated with a Milli-Q water system. The temperature of the outflow water was measured for temperature-dependent water absorption corrections. Corrections for the *in situ* temperature and salinity effects on optical properties of water were applied as described by Pegau *et al.* (2003). All absorption measurements and water calibrations were normalized to a constant temperature to account for the temperature dependence of the absorption coefficient of pure water. The temperature corrections were

6) $a_{tcorr}(\propto) = a_{meas}(\propto) - (T_i - T_{norm}) \propto_t (\propto)$

7) $c_{tcorr}(\propto) = c_{meas}(\propto) - (T_i - T_{norm}) \propto_t (\propto)$

where a_{tcorr} and c_{tcorr} are the absorption and attenuation corrected for changes in water temperature, a_{meas} and c_{meas} are the measured absorption and attenuation at *in situ* temperature, T_i is the *in situ* temperature, T_{norm} is the temperature that the absorption and attenuation is being normalized to, and $\propto_t$ is the wavelength specific slope from Sullivan *et al.* (2006). A salinity correction was necessary due to the absorption by dissolved salts and refractive index errors between seawater and freshwater that can distort the optical path. Salinity corrections were

8) $a_{tscorr}(\propto) = a_{tcorr}(\propto) - S_i \propto_{s,a} (\propto)$

9) $c_{tscorr}(\propto) = c_{tcorr}(\propto) - S_i \propto_{s,c} (\propto)$

where a_{tscorr} and c_{tscorr} are the absorption and attenuation corrected for temperature and salinity effects, S_i is the salinity of the sample, $\propto_{s,a}$ and $\propto_{s,c}$ are the wavelength specific slopes for absorption and attenuation from Sullivan *et al.* (2006). The scattering correction between true absorption and absorption measured by the reflective tube of the ac-s was applied as described by Zaneveld et al. (1994). The assumption is that there is minimal absorption at 717.7 nm for the absorption channel of ac-s and that the scattering error is independent of wavelength. Corrected total absorption coefficients, $a_t(\propto)$, were obtained from

10) $a_t(\psi) = a_{tscorr}(\psi) - \{a_{tscorr}(717.7) / [c_{tscorr}(720.3) - a_{tscorr}(717.7)]\}[c_{tscorr}(\psi) - a_{tscorr}(\psi)]$.

All data within 1m bins over depth z were averaged to keep the coefficient of variation of the average data < 10%.

2.8 Spectrophotometric and Fluorometric Analysis from Discrete Water Samples

Absorption analysis samples were also collected from Niskin bottles at each depth, filtered through duplicate Whatman GF/F filters, placed in Histoprep capsules, and flash frozen in liquid nitrogen until analysis in the laboratory at NASA GSFC Wallops Flight Facility. Absorption measurements were performed on a Perkin Elmer LS800 UV/VIS Spectrophotometer. The instrument was background corrected before each batch of six samples, and baselines were run on filtered seawater. Initial samples were run using a filtered seawater blank for comparison to determine the absorption by all particles ($a_{p,\ spectrophotometer}$).

Duplicate Chl *a* samples were filtered on 25 mm GF/F filters, placed in histopreps and flash frozen until analysis. Pigments were filtered in duplication on 25 mm GF/F filters, placed in histopreps and flash frozen in liquid nitrogen immediately. For analysis, chlorophyll samples were brought to room temperature and 7 mL of 90% acetone was added. Samples were placed in the freezer to be analyzed in less than 24 hours. Samples were read on a Turner 10-AU fluorometer using the Welschmeyer technique (1994).

Section 3

Results & Discussion

3.1 Description of User-specific C Program

The dh4decode program runs from the command line and takes a number of parameters to specify the configuration files needed for each sensor and the station's latitude.

dh4decode -l LAT -9 ac9SN.dev -s acsSN.dev -3 fl3SN.dev -v vsfSN.dev

-l latitude : specify the station's latitude

-9 ac9SN.dev : specify ac9 device file

-s acsSN.dev : specify acs device file

-v vsfSN.dev : specify Eco VSF device file

-3 fl3SN.dev : specify Eco FL3 device file

The program first searches for the synchronization bits that signal the start of a DH-4 record. The following DH-4 record is then read into a structure. Each DH-4 record contains a header and body. The header provides a time stamp, record count, and the amount of data from each sensor in the body of the record. This record is then passed to specialized routines for each sensor.

These specialized routines extract their portion of the data from the DH-4 record and search for the synchronization bits that signal the start of their record. After the start of the record marker is found, the sensor record is rebuilt. One complete record for a sensor may be spread across multiple DH-4 records or one DH-4 record may contain more than one record for the sensor. After a complete sensor record is built, it is passed off to another routine to apply the corrections to the raw data for that sensor.

3.1.1 CTD

The CTD record arrives to the DH-4 approximately twice every 100ms and provides depth, temperature, conductivity, and salinity data. The CTD record is stored as ascii text inside the DH4 record.

Depth is computed using the raw CTD pressure value and the latitude where the measurement was taken.

Temperature and conductivity are taken directly from the CTD record.

Salinity is computed using the raw CTD temperature, conductivity, and pressure values.

Both salinity and depth are computed using algorithms from the help section of the Sea-Bird software, the manufacturer of the CTD. See Appendixes A and B, respectively, for the code.

3.1.2 ac-s

The raw data is stored in big-endian byte order and packed into a structure with mixed data types. The ac-s record is processed according to the WET Labs ac-s User's Guide, Revision F, Section 3 “Data Processing” and Appendix A. The raw data is converted to engineering units and corrected according to the supplied configuration file.

The timestamp from the first DH-4 record is subtracted from the DH-4 record that contains the end of the ac-s record. This value is used as the timestamp in the output record. The data rate for the ac-s is one record every ~ 250 ms and takes 2 to 3 DH-4 records to recreate a single ac-s record. The DH-4 data rate is one record every ~ 100 ms.

Values of 99.9999 are output if the ratio of signal / reference is less that 0.0005.

3.1.3 ac-9

The raw data is stored in little-endian byte order and packed into a structure with mixed data types. Our current systems require these words to be byte swapped before processing. The ac-9 record is processed according to the WET Labs ac-9 User's Guide, Revision O, Section 3 “Data Processing”. The raw data is converted to engineering units and corrected according to the supplied configuration file.

The timestamp from the first DH-4 record is subtracted from the DH-4 record that contains the end of the ac-9 record; 1400 msec is subtracted from this value. The data rate for the ac-9 record every ~1700 msec and takes ~17 DH-4 records to recreate a single ac-9 record. Each ac-9 record contains ten sub-records and has an internal timestamp for each of these. That timestamp is then applied to the record time computed above and written to the output file for each sub-record.

Values of 99.9999 are output if the ratio of signal / reference is less that 0.0005.

3.1.4 ISUS

The ISUS data is stored as ascii text inside the DH-4 record. Each record is written out exactly as supplied along with the time stamp from the DH-4.

3.1.5 Eco FL3 and VSF

Data from the Eco triplet fluorometer and Eco VSF is processed in the same manner. The data is stored as ascii text inside the DH-4 records. Using their device configuration file, the output is converted to engineering units using the following linear equation:

Output (eng) = scale factor (Output Counts - Offset)

3.2 Validation of User-specific C Program Processing DH-4

We have developed an in-house processing program. The correctness of the output has been verified against the output from WAP using multiple BIOME V data sets. The same data sets were processed with both WAP and our program and the results

were compared using the Unix 'diff' command. In most cases the results were an exact match. Where there were differences, they were minor. The ac-9 data showed an exact match, with the exception of the timestamp that would sometimes differ by 100 ms. A plot of the time difference is shown in Appendix D.

The ac-s data has a difference from the WAP values by, at most, +/- .00003. No explanation was determined for this. We increased the number of decimal places output by our program by one place to determine if the difference could be explained by a difference in rounding vs. truncating, but that didn't seem to be the case. Appendix E contains a graph showing the differences between four selected fields when both program output results to five decimal places. Appendix E shows our data being plotted against the same WAP output. The attenuation at 401 (C401) and 600.4 nm (C600.4) and absorption at 399.8 (A399.8), and 601.4 nm (A601.4) from DH-4 were selected as a representative sample across the data set for the absorption and attenuation channels of ac-s 017.

3.3 Water offset

Water offset values by ac-s were obtained once a day by averaging absorption [$a_{ac\text{-}s}(\psi)$] and attenuation spectra [$c_{ac\text{-}s}(\psi)$] using Milli-Q water onboard the ship from October 30 to November 1, 2006. The minimum $a_{ac\text{-}s}(\psi)$ and $c_{ac\text{-}s}(\psi)$ of water offset was from -0.0154 to 0.0240 and from -0.0203 to 0.0234, respectively, for November 1, 2006 (Figure 3-1). Milli-Q water offset for *ac-s* calibration was applied the minimum $a_{ac\text{-}s}(\psi)$ and $c_{ac\text{-}s}(\psi)$ for November 1, 2006 as shown in Appendix A.

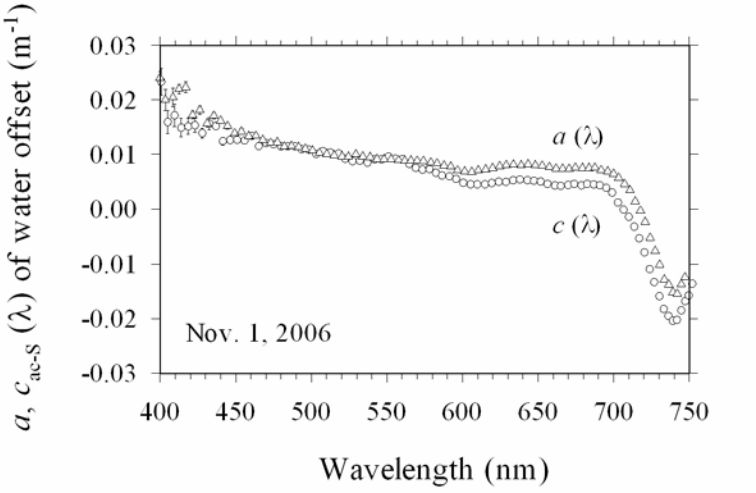

Figure 3-1 Absorption [$a_{ac\text{-}s}(\psi)$] and attenuation spectra with the *ac-s* [$c_{ac\text{-}s}(\psi)$] for Milli-Q water offset on November 1, 2006 during the BIOME V cruise. Average and standard deviation bars are shown. The Milli-Q water offset during the BIOME V cruise was applied on November 1, 2006 as shown in Appendix A.

3.4 Analysis of BIOME V ac-s Data

The profile of temperature and salinity at Station 1 on the BIOME V is shown in Figure 3-2. The raw absorption data is influenced by (1) temperature and salinity effects of pure water and (2) scattering effect which is introduced because all of the scattered light is not measured by the absorption detector.

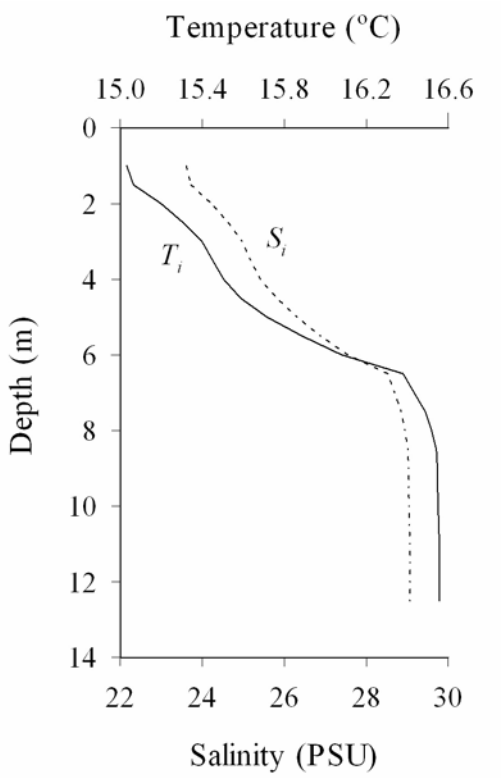

Figure 3-2 Temperature (T_i) and Salinity (S_i) profiles at Station 1 on the BIOME V cruise

Below (Figure 3-3), we present the raw total attenuation [$c_{\text{row, t, ac-s}}(\psi)$] and absorption [$a_{\text{row, t, ac-s}}(\psi)$] spectra with the ac-s measurements from depth 0.5 to 12.2 m at Station 1 on the BIOME V cruise.

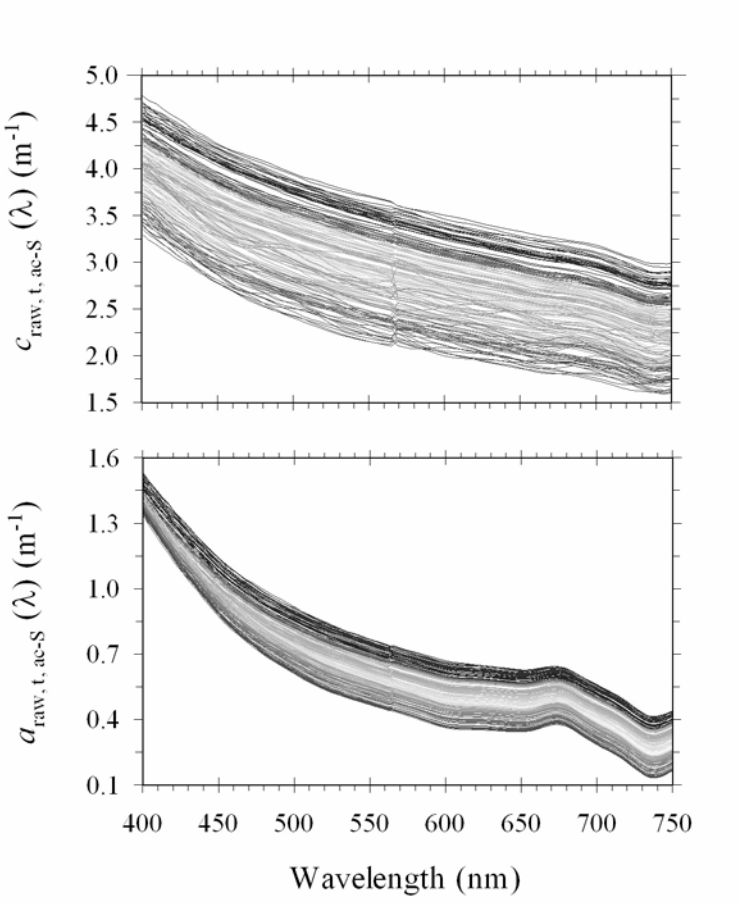

Figure 3-3 The row total attenuation [$c_{\text{row, t, ac-s}}(\psi)$] and absorption [$a_{\text{row, t, ac-s}}(\psi)$] spectra with the ac-s measurements from depth 0.5 to 12.2 m at Station 1 on the BIOME V cruise. These are 185 superimposed c $_{\text{row, t, ac-s}}$ (l) and a $_{\text{row, t, ac-s}}$ (l) spectra.

The salinity dependence of the absorption of optically pure water showed a broader band minimum from 716 to 724 nm (Sullivan *et al.* 2006). The $\psi_{s,c}$ and $\psi_{s,a}$ indicated strong variations in the salinity coefficient in the near infrared and a broader minimum from 716 to 724 nm (Figure 3-4). Since the ac-s is calibrated with fresh water, the salinity effect is quite large. We assumed that there is minimal absorption at 717.7 nm for the absorption channel of the ac-s, assuming that any excess values were due to scattering, or remaining calibration residues.

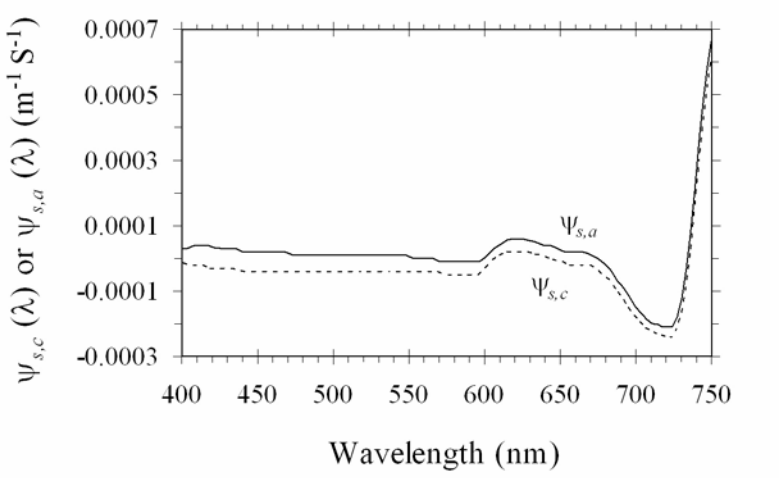

Figure 3-4 The wavelength specific slope of salinity for absorption ($\psi_{s,a}$) and attenuation ($\psi_{s,c}$) as determined by Sullivan *et al.* (2006)

The total attenuation [$c_{t,\ ac\text{-}s}\ (\psi)$] and absorption [$a_{t,\ ac\text{-}s}\ (\psi)$] spectra corrected for temperature, salinity and scattering effects with ac-s measurements are presented (Figure 3-5) from depth 0.5 to 12.2 m at Station 1 on the BIOME V cruise.

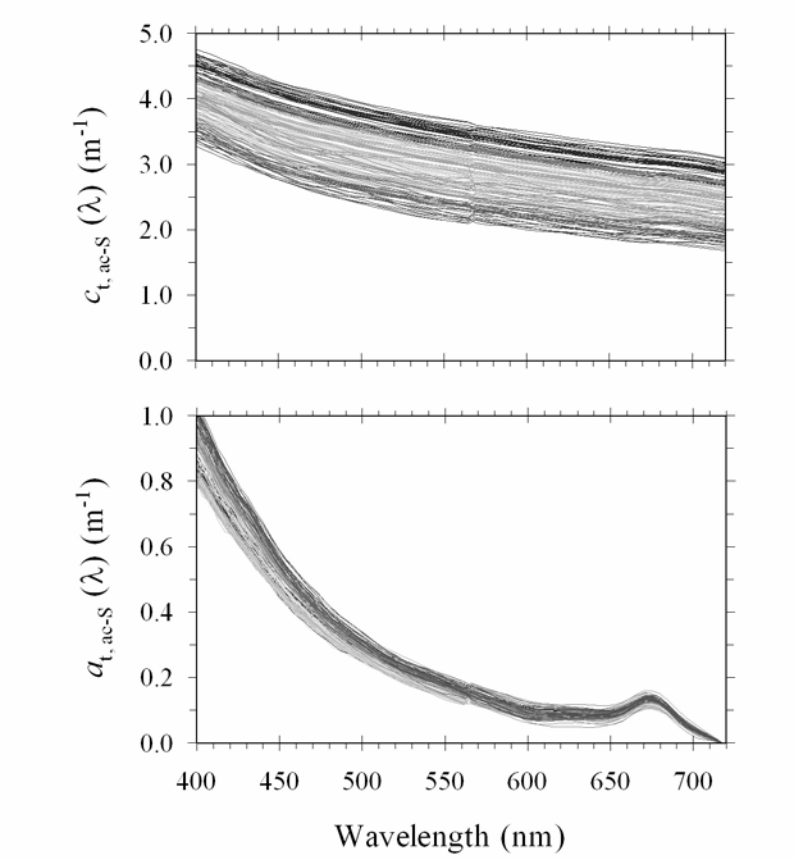

Figure 3-5 The total attenuation [$c_{t,\ ac\text{-}s}\ (\psi)$] and absorption [$a_{t,\ ac\text{-}s}\ (\psi)$] spectra corrected for temperature, salinity and scattering effects measured by the ac-s from depth 0.5 to 12.2 m at Station 1 on the BIOME V cruise. These are 185 superimposed $c_{t,\ ac\text{-}s}\ (\psi)$ and $a_{t,\ ac\text{-}s}\ (\psi)$ spectra.

3.5 Spectral *a* (ψ) and *c* (ψ)

Total absorption spectra for *in situ* ac-s measurements [$a_{t,\ ac\text{-}s}(\psi)$] and particulate absorption spectra by spectrophotometric analysis of discrete water samples [$a_{p,\ spectrophotometer}(\psi)$] with depth 2 m at Stations 1, 4, and 7 during the BIOME V cruise are shown in Figure 3-6.

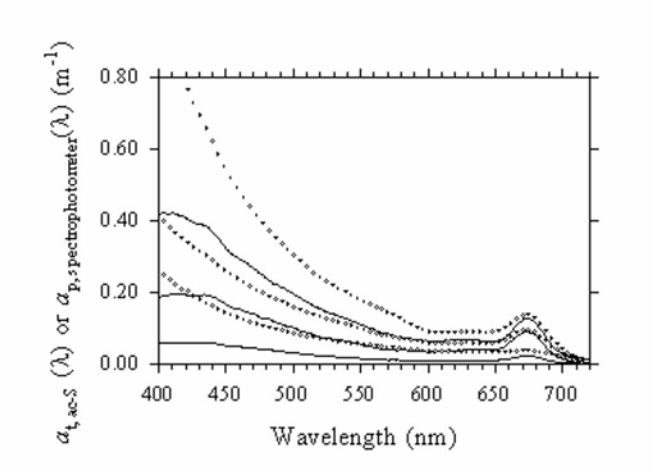

Figure 3-6 Total absorption spectra for the ac-s measurements [$a_{t,\ ac\text{-}s}(\psi)$, Symbols] and particulate absorption spectra by the spectrophotometric analysis from discrete water samples [$a_{p,\ spectrophotometer}(\psi)$, lines] at depth 2 m at Stations 1, 4, and 7 during the BIOME V cruise

At 440 nm, where the absorption peak is for chl *a* and accessory pigments, the $a_{t,\ ac\text{-}s}$ (440) was significantly higher than that for $a_{p,\ spectrophotometer}$ (440) because of the effect of absorption in CDOM. At 674 nm, where the absorption peak is due mostly to chl *a*, the $a_{t,\ ac\text{-}s}$ (674) was significantly correlated to $a_{p,\ spectrophotometer}$ (674) ($y = 1.012\ x$, $r^2 = 0.81$, $n = 30$) (Figure 3-7). The other side, the $a_{t,\ ac\text{-}s}$ (674) ,was high compared to $a_{p,\ spectrophotometer}$ (674) because of the absorption by CDOM.

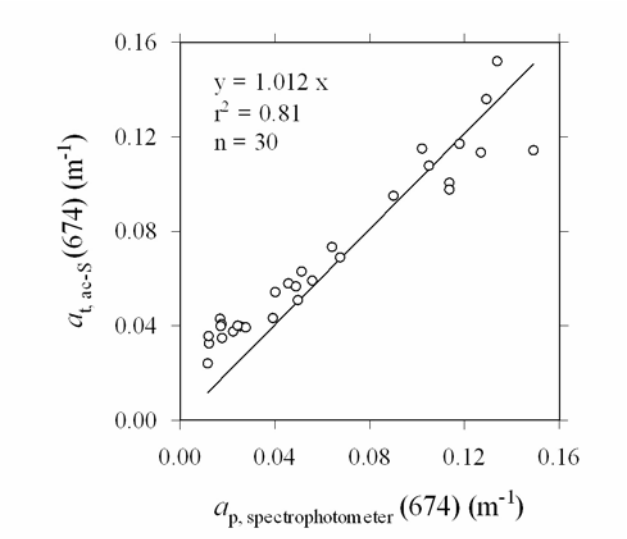

Figure 3-7 Relationship of absorption at 674 nm between the ac-s measurement [$a_{t,\ ac\text{-}s}$ (674)] and the spectrophotometric analysis of discrete water samples [$a_{p,\ spectrophotometer}$ (674)] at all stations during the BIOME V cruise.

Attenuation spectra with *in situ* ac-s measurement [$c_{t,\ ac\text{-}s}\ (\psi)$] at depth 2 m in all stations during the BIOME V cruise are exhibited in Figure 3-8. The $c_{t,\ ac\text{-}s}\ (\psi)$ decreased from coastal water at Station 1 to offshore water at Station 9 and increased with decrease of wavelength.

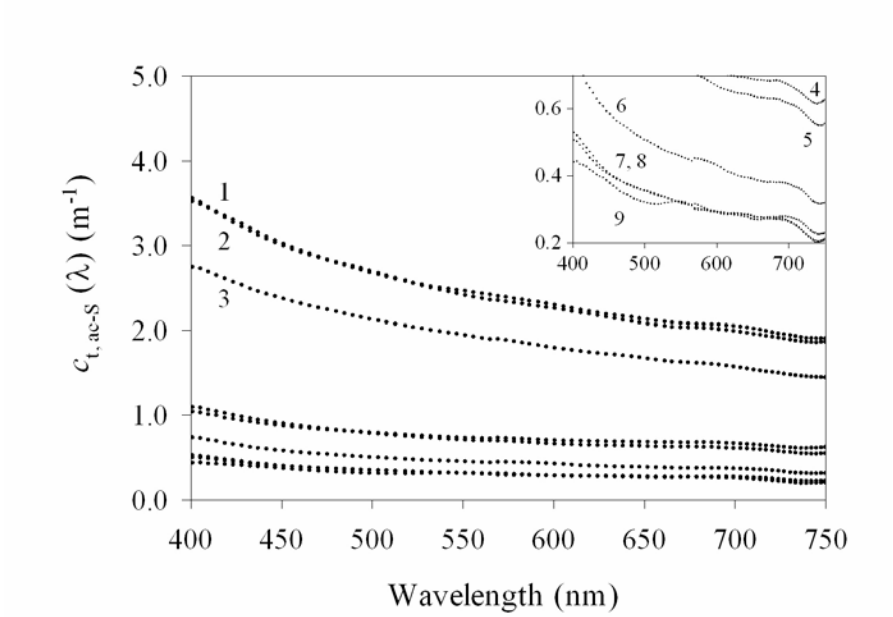

Figure 3-8 Mean attenuation spectra with ac-s measurement [$c_{t,\ ac\text{-}s}\ (\psi)$] at depth 2 m at all stations during the BIOME V cruise. The numbers inside the figure indicate the cruise station number.

3.5.1 Vertical profile for *a* (ψ) and *c* (ψ)

Vertical profiles of total absorption coefficients at 440 [$a_{t,\ ac\text{-}s}\ (440)$] and 674 nm [$a_{t,\ ac\text{-}s}\ (674)$] and total attenuation coefficients at 440 nm [$c_{t,\ ac\text{-}s}\ (440)$] and 661 nm [$c_{t,\ ac\text{-}s}\ (661)$] measured by the ac-s at nine stations during the BIOME V cruise are shown in Figure 3-9 and Figure 3-10.

The $a_{t,\ ac\text{-}s}\ (440)$ ranged from 0.35 to 0.99 m^{-1} at Stations 1 to 3 in the inshore region and from 0.085 to 0.51 m^{-1} at Stations 4 to 9 in the offshore region. The $c_{t,\ ac\text{-}s}\ (440)$ ranged from 1.7 to 4.2 m^{-1} at Stations 1 to 3 in the inshore region and 0.15 to 2.84 m^{-1} at Stations 4 to 9 in the offshore region. These results were within the range of the $a_{t,\ spectrophotometer}\ (443)$ and $c_{t,\ spectrophotometer}\ (443)$ by the spectrophotometric method at 110 stations in the Mid-Atlantic Bight (MAB) reported by Magnuson *et al.* (2004). They have reported the $a_{t,\ spectrophotometer}\ (443)$ ranged from 0.093 to 1.6 m^{-1} in the inshore MAB and from 0.032 to 0.37 m^{-1} in the offshore MAB, respectively. They also report that the $c_{t,\ spectrophotometer}\ (443)$ ranged from 0.493 to 11.1 m^{-1} in the inshore MAB and from 0.33 to 7.2 m^{-1} in the offshore MAB. The vertical variation in

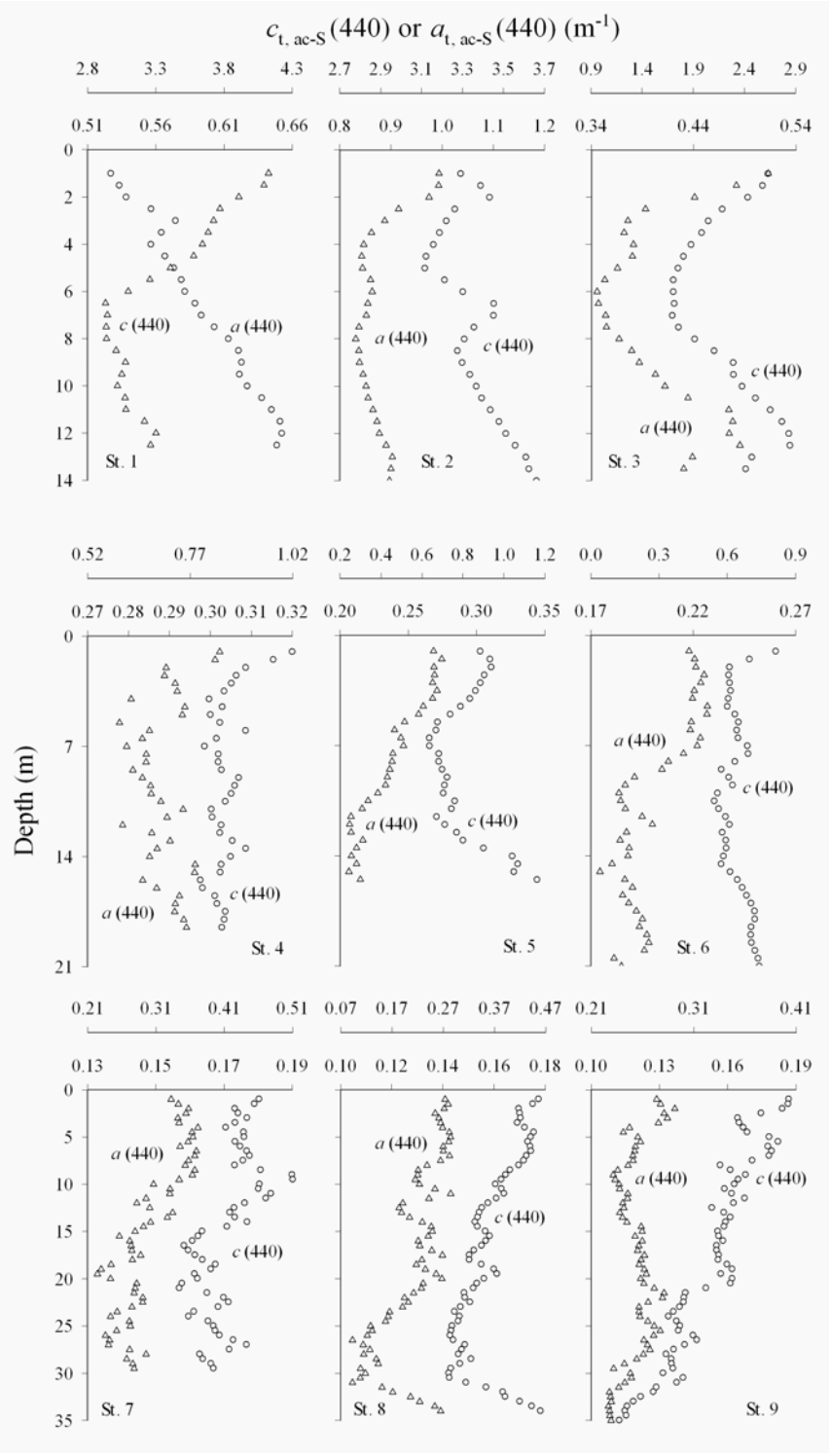

Figure 3-9 Vertical profiles of the total attenuation coefficient [$c_{t,\,ac\text{-}s}$ (440)] and the total absorption coefficient at 440 nm [$a_{t,\,ac\text{-}s}$ (440)] as measured by the ac-s at Stations 1 through 9 during the BIOME V cruise.

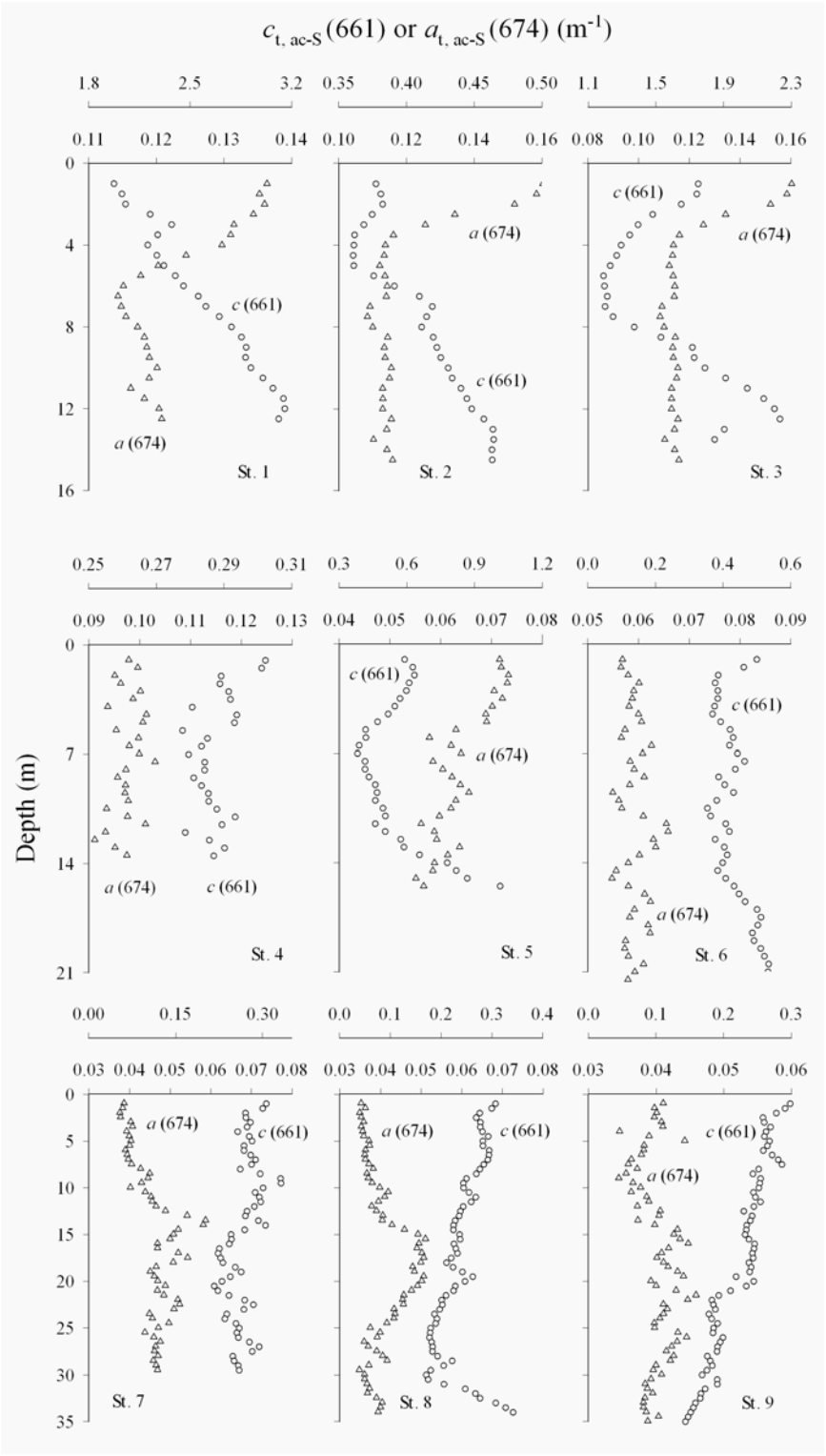

Figure 3-10 Vertical profiles of the total attenuation coefficient at 661 nm [$c_{t,\,ac\text{-}s}(661)$] and the total absorption coefficient at 674 nm as measured by the ac-s [$a_{t,\,ac\text{-}s}(674)$] at Stations 1 to 9 during the BIOME V cruise.

$a_{t,ac\text{-}s}$ (440) might be due mainly to CDOM, phytoplankton chl *a* and accessory pigment absorption and detritus as described in equation (1).

The $a_{t,\ ac\text{-}s}$ (674) and $c_{t,\ ac\text{-}s}$ (661) are plotted due to their importance in estimating phytoplankton chl *a* absorption and POC concentration, respectively (e.g. Gardner *et al*. 1993) as shown in Figure 3-6. Most of the large changes observed in the magnitude of $a_{t,\ ac\text{-}s}$ (674) were due to the phytoplankton fraction of chl *a*. The significant relationship between $a_{t,\ ac\text{-}s}$ (674) and chl *a* (Figure 3-11) was indicated as:

11) Chl $a = 83.0\ a_{t,\ ac\text{-}s}\ (674)^{1.13}$, $r^2 = 0.81$.

Relationships between the chl *a* concentration and *a* (674 or 676) are generally modeled using a power function to account for the decrease of the chl *a*-specific absorption coefficient with the increase in chl *a* due to the package effect and pigment composition (Bricaud *et al*. 1995).

Vertical distribution of $c_{t,\ ac\text{-}s}$ (661) due to the POC was not dependent on that of $a_{t,\ ac\text{-}s}$ (674) due to the chl *a*. These results implied that the vertical variation in the ratio of carbon to chl *a* is due to phytoplankton photoadaptation.

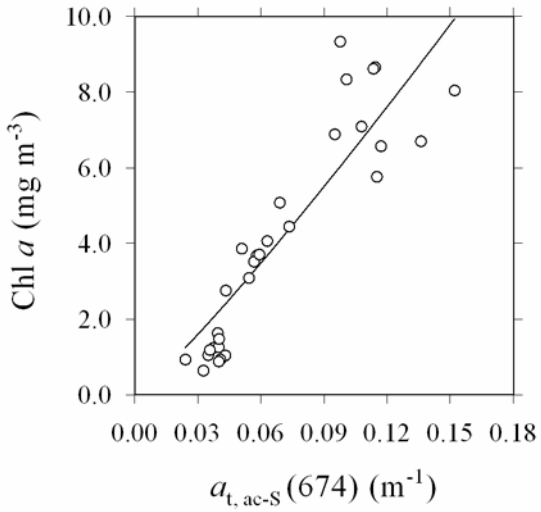

Figure 3-11 Relationship between the total absorption coefficient measured by the ac-s at 674 nm [$a_{t,\ ac\text{-}s}$ (674)] and the fluorometer-determined chlorophyll *a* concentration of discrete water samples (Chl *a*).

Section 4

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Appendix A
Milli-Q Water Offset

λ (nm)	$c_{ac\text{-}s}(\lambda)$ (m^{-1})	$\sigma_{c(\lambda)}$ (m^{-1})	λ (nm)	$c_{ac\text{-}s}(\lambda)$ (m^{-1})	$\sigma_{c(\lambda)}$ (m^{-1})	λ (nm)	$a_{ac\text{-}s}(\lambda)$ (m^{-1})	$\sigma_{a(\lambda)}$ (m^{-1})	λ (nm)	$a_{ac\text{-}s}(\lambda)$ (m^{-1})	$\sigma_{a(\lambda)}$ (m^{-1})
400.7	0.0234	0.0025	595.7	0.0056	0.0001	399.8	0.0240	0.0012	592.2	0.0078	0.0001
405.0	0.0160	0.0021	600.4	0.0048	0.0001	403.5	0.0200	0.0020	596.7	0.0071	0.0001
409.4	0.0172	0.0021	605.3	0.0046	0.0001	408.4	0.0205	0.0017	601.4	0.0069	0.0001
413.9	0.0150	0.0017	609.8	0.0046	0.0001	412.5	0.0220	0.0009	606.1	0.0068	0.0001
418.5	0.0152	0.0015	614.7	0.0046	0.0001	416.9	0.0223	0.0010	610.5	0.0071	0.0001
423.0	0.0154	0.0013	619.4	0.0048	0.0001	421.5	0.0173	0.0007	615.4	0.0073	0.0001
427.8	0.0139	0.0009	624.0	0.0050	0.0001	426.3	0.0182	0.0007	619.9	0.0075	0.0001
432.5	0.0156	0.0011	628.7	0.0050	0.0001	431.1	0.0157	0.0007	624.7	0.0078	0.0001
436.8	0.0153	0.0006	633.4	0.0053	0.0001	435.6	0.0171	0.0006	629.0	0.0080	0.0001
441.4	0.0125	0.0007	638.0	0.0054	0.0001	440.0	0.0162	0.0005	633.7	0.0081	0.0001
446.2	0.0127	0.0005	642.8	0.0053	0.0001	444.6	0.0152	0.0005	638.8	0.0080	0.0001
450.9	0.0127	0.0006	647.1	0.0052	0.0001	449.3	0.0139	0.0003	643.5	0.0082	0.0001
455.7	0.0126	0.0006	651.6	0.0051	0.0001	453.8	0.0142	0.0005	648.1	0.0080	0.0001
460.4	0.0134	0.0006	656.2	0.0047	0.0001	458.7	0.0133	0.0004	652.7	0.0079	0.0001
465.2	0.0116	0.0005	661.1	0.0044	0.0001	463.4	0.0134	0.0004	657.5	0.0077	0.0001
470.1	0.0121	0.0002	665.0	0.0043	0.0001	468.0	0.0127	0.0003	661.9	0.0074	0.0001
475.0	0.0119	0.0005	669.8	0.0045	0.0001	473.1	0.0121	0.0003	666.2	0.0074	0.0001
479.9	0.0115	0.0004	673.9	0.0046	0.0001	477.6	0.0123	0.0002	670.6	0.0073	0.0001
484.5	0.0115	0.0003	678.6	0.0044	0.0001	482.2	0.0115	0.0002	674.7	0.0076	0.0001
489.0	0.0115	0.0003	682.5	0.0046	0.0001	486.9	0.0115	0.0002	679.4	0.0075	0.0001
493.5	0.0110	0.0003	686.8	0.0045	0.0001	491.6	0.0114	0.0003	683.7	0.0076	0.0001
498.2	0.0109	0.0003	690.8	0.0044	0.0002	496.1	0.0111	0.0002	687.6	0.0076	0.0001
503.1	0.0101	0.0003	695.0	0.0039	0.0001	500.8	0.0107	0.0002	691.8	0.0072	0.0001
507.6	0.0106	0.0002	698.9	0.0030	0.0001	505.4	0.0103	0.0002	696.0	0.0069	0.0001
512.6	0.0104	0.0002	702.8	0.0012	0.0002	510.2	0.0101	0.0001	699.9	0.0065	0.0001
518.0	0.0102	0.0002	706.5	-0.0001	0.0002	515.1	0.0099	0.0002	703.4	0.0057	0.0001
522.3	0.0093	0.0002	710.0	-0.0014	0.0002	520.3	0.0096	0.0002	707.3	0.0046	0.0001
527.2	0.0088	0.0002	713.6	-0.0032	0.0002	524.6	0.0096	0.0002	710.8	0.0034	0.0001
532.0	0.0089	0.0002	716.9	-0.0053	0.0002	529.4	0.0100	0.0002	714.2	0.0014	0.0002
537.0	0.0085	0.0002	720.3	-0.0078	0.0002	534.1	0.0096	0.0001	717.7	-0.0003	0.0002
541.8	0.0092	0.0002	723.7	-0.0109	0.0002	538.9	0.0096	0.0001	720.9	-0.0024	0.0002
546.4	0.0091	0.0002	726.8	-0.0132	0.0003	543.5	0.0092	0.0001	724.1	-0.0053	0.0002
551.0	0.0096	0.0002	730.2	-0.0158	0.0003	548.1	0.0091	0.0001	727.5	-0.0076	0.0003
555.5	0.0092	0.0002	733.1	-0.0182	0.0003	552.9	0.0091	0.0001	730.4	-0.0101	0.0003
560.3	0.0092	0.0002	736.2	-0.0195	0.0002	557.7	0.0090	0.0001	733.5	-0.0128	0.0003
564.7	0.0083	0.0002	739.1	-0.0203	0.0003	561.8	0.0089	0.0001	736.5	-0.0137	0.0003
569.1	0.0076	0.0002	741.8	-0.0202	0.0003	565.9	0.0089	0.0001	739.2	-0.0151	0.0003
573.5	0.0073	0.0001	744.6	-0.0184	0.0004	570.0	0.0089	0.0001	742.1	-0.0154	0.0003
578.0	0.0073	0.0001	747.2	-0.0168	0.0004	574.2	0.0088	0.0001	744.8	-0.0137	0.0003
582.4	0.0067	0.0001	749.5	-0.0157	0.0004	579.0	0.0085	0.0001	747.3	-0.0124	0.0004
586.4	0.0062	0.0001	752.0	-0.0136	0.0004	583.2	0.0084	0.0001	749.8	-0.0109	0.0004
591.3	0.0060	0.0001				587.8	0.0080	0.0001			

Table A-1 Offset of Milli-Q water for the attenuation, $c_{ac\text{-}s}(\lambda)$, and absorption, $a_{ac\text{-}s}(\lambda)$, with the ac-s. Standard deviations, $\lambda_{c(\lambda)}$ and $\lambda_{a(\lambda)}$, for each measured value are also given.

Appendix B
Salinity Calculations

Formulas for the computation of salinity, density, potential temperature, specific volume anomaly, and sound velocity were obtained from "Algorithms for Computation of Fundamental Properties of Seawater", by N.P. Fofonoff and R.C Millard Jr.; Unesco technical papers in *Marine Science* #44, 1983.

The temperature used for calculating derived variables is IPTS-68. Following the recommendation of JPOTS, T68 is assumed to be 1.00024 * T90 (-2 to 35 °C).

salinity = [PSU]

(Salinity is PSS-78.)

C Computer Code

```
// Constants

static double

    A1 =  2.070e-5,
    A2 = -6.370e-10,
    A3 =  3.989e-15,
    B1 =  3.426e-2,
    B2 =  4.464e-4,
    B3 =  4.215e-1,
    B4 = -3.107e-3,
    C0 =  6.766097e-1,
    C1 =  2.00564e-2,
    C2 =  1.104259e-4,
    C3 = -6.9698e-7,
    C4 =  1.0031e-9;

static double a[6] = { 0.0080, -0.1692, 25.3851, 14.0941, -7.0261, 2.7081 };
static double b[6] = { 0.0005, -0.0056, -0.0066, -0.0375, 0.0636, -0.0144 };

// compute salinity

// C = conductivity S/m, T = temperature deg C ITPS-68, P = pressure in decibars

double Salinity(double C, double T, double P) {

 double R, RT, RP, temp, sum1, sum2, result, val;

 int i;

 if (C <= 0.0)

  result = 0.0;

 else {
```

```
  C *= 10.0;      /* convert Siemens/meter to mmhos/cm */
  R = C / 42.914;
  val = 1 + B1 * T + B2 * T * T + B3 * R + B4 * R * T;
  if (val)  RP = 1 + (P * (A1 + P * (A2 + P * A3))) / val;
  val = RP * (C0 + (T * (C1 + T * (C2 + T * (C3 + T * C4)))));
  if (val)  RT = R / val;
  if (RT <= 0.0)  RT = 0.000001;
  sum1 = sum2 = 0.0;
  for (i = 0;i < 6;i++) {
    temp = pow(RT, (double)i/2.0);
    sum1 += a[i] * temp;
    sum2 += b[i] * temp;
  }
  val = 1.0 + 0.0162 * (T - 15.0);
  if (val)
    result = sum1 + sum2 * (T - 15.0) / val;
  else
    result = -99.;
 }
 return result;
}
```

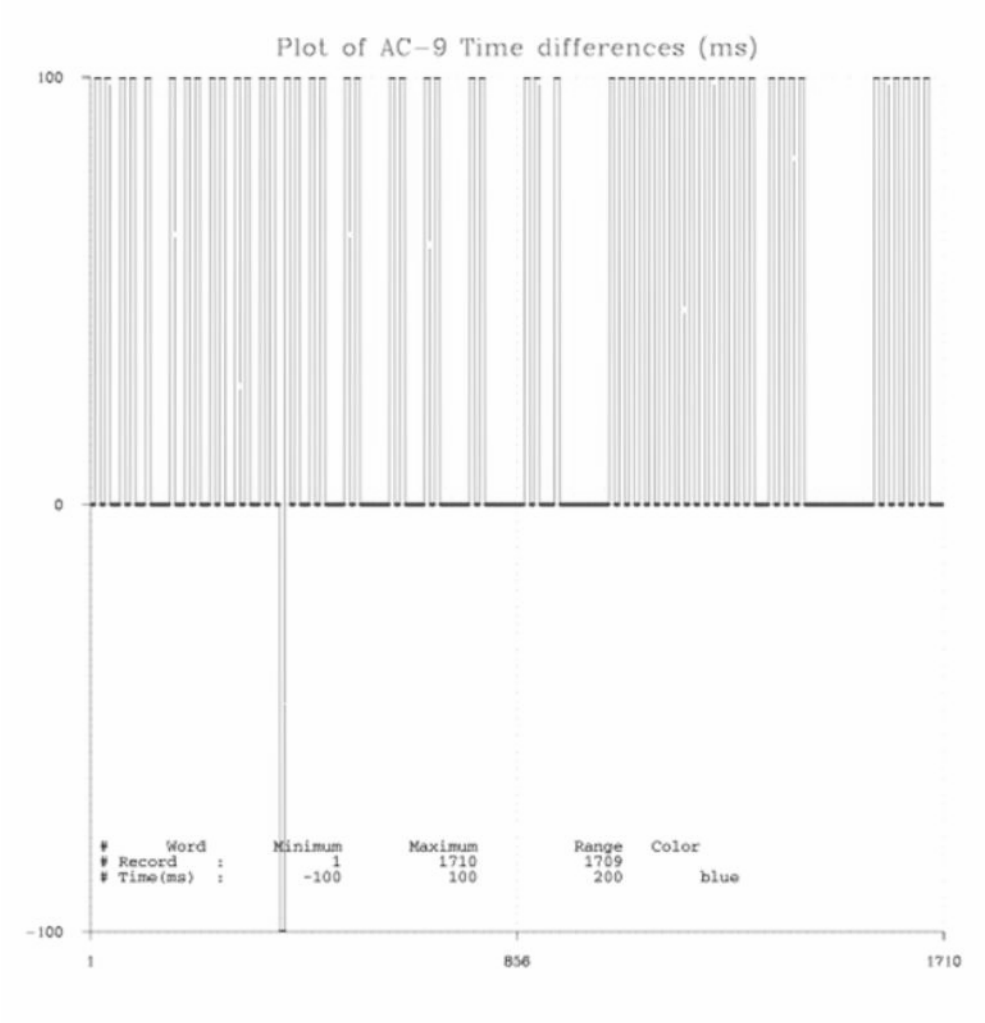
Appendix C
Depth Calculations

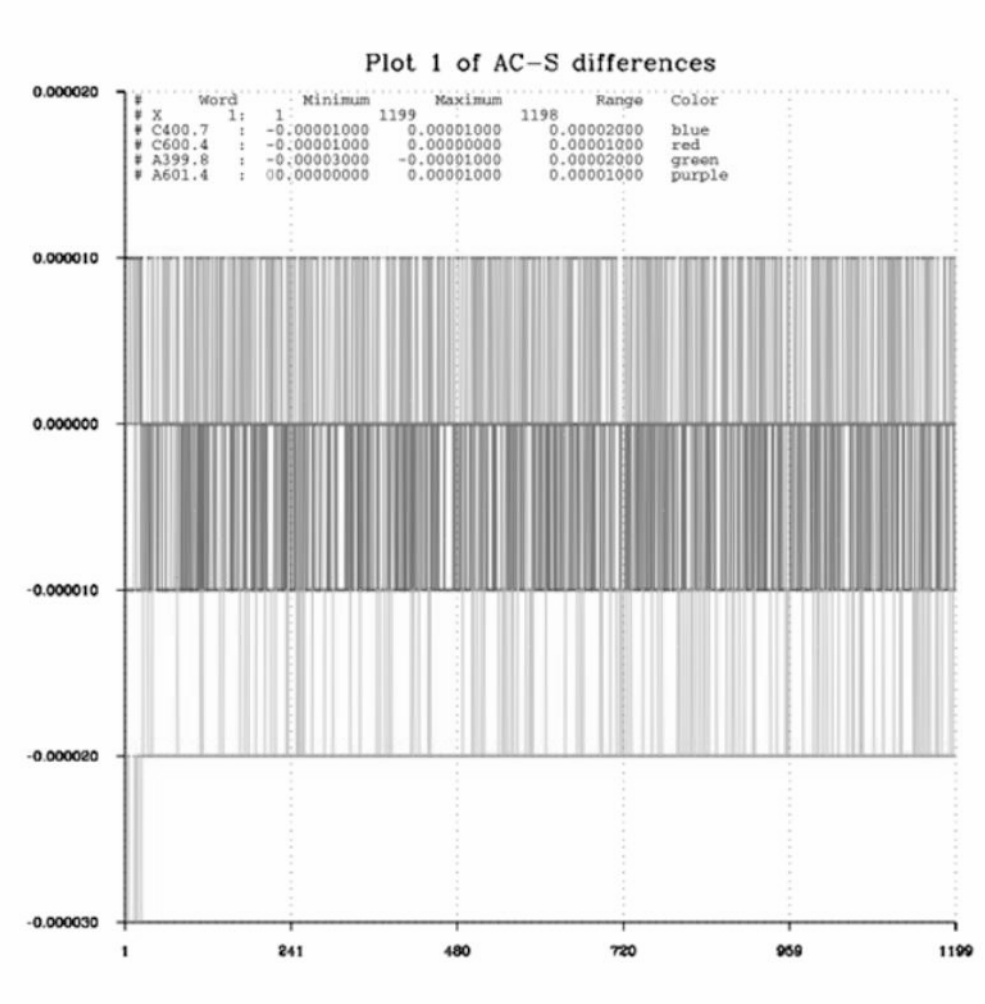
C Computer Code

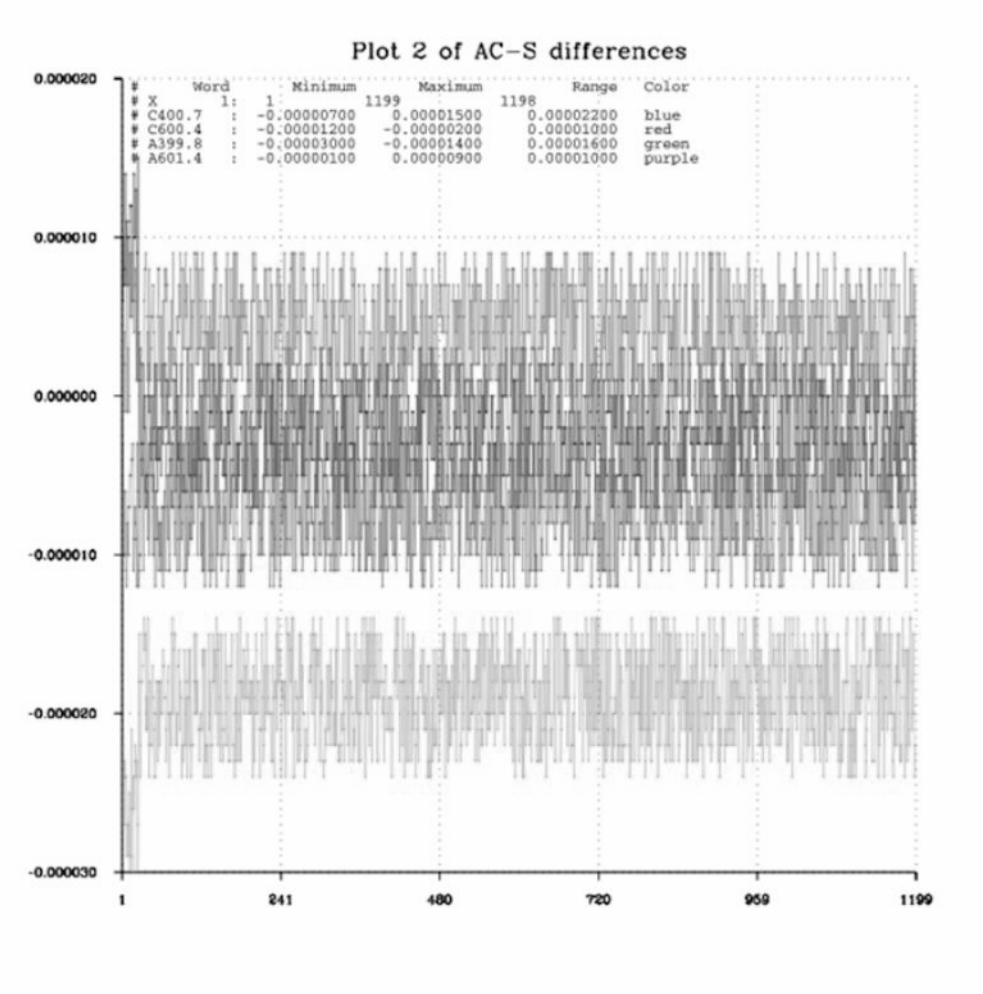
```
// depth =     [m]
// Depth calculation:
// dtype = fresh water or salt water
// p = pressure in decibars,
// latitude in degrees
double Depth(int dtype, double p, double latitude) {
 double x, d, gr;

 if (dtype == FreshWater)          // fresh water
   d = p * 1.019716;
 else {                            // salt water
   x  = sin(latitude / 57.29578);
   x *= x;
   gr = 9.780318 * (1.0 + (5.2788e-3 + 2.36e-5 * x) * x) + 1.092e-6 * p;
   d  = (((-1.82e-15 * p + 2.279e-10) * p - 2.2512e-5) * p + 9.72659) * p;
   if (gr)  d /= gr;
 }
 return(d);
}
```

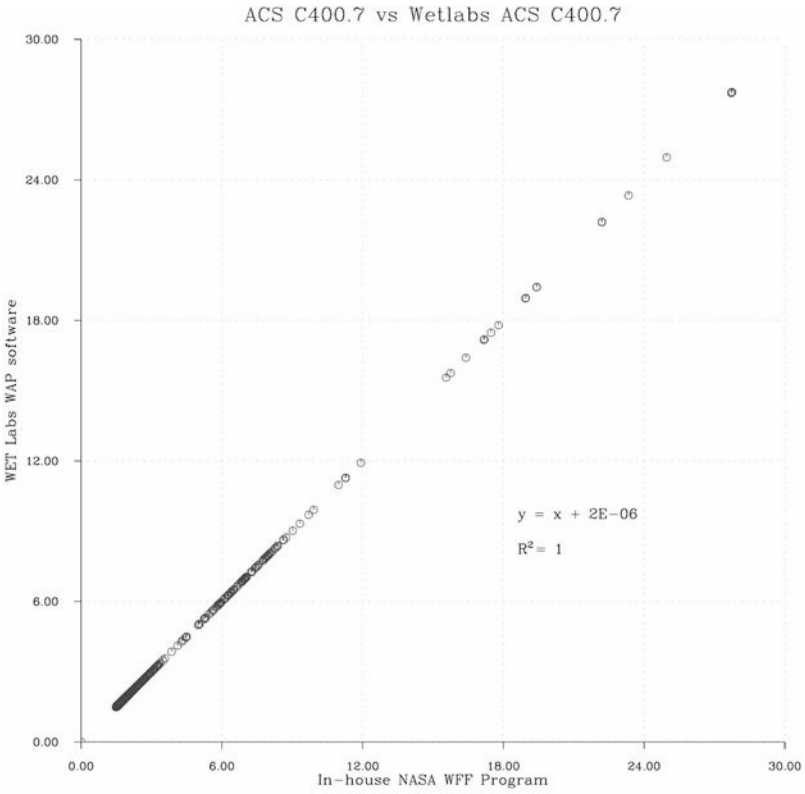
Appendix D
AC Differences

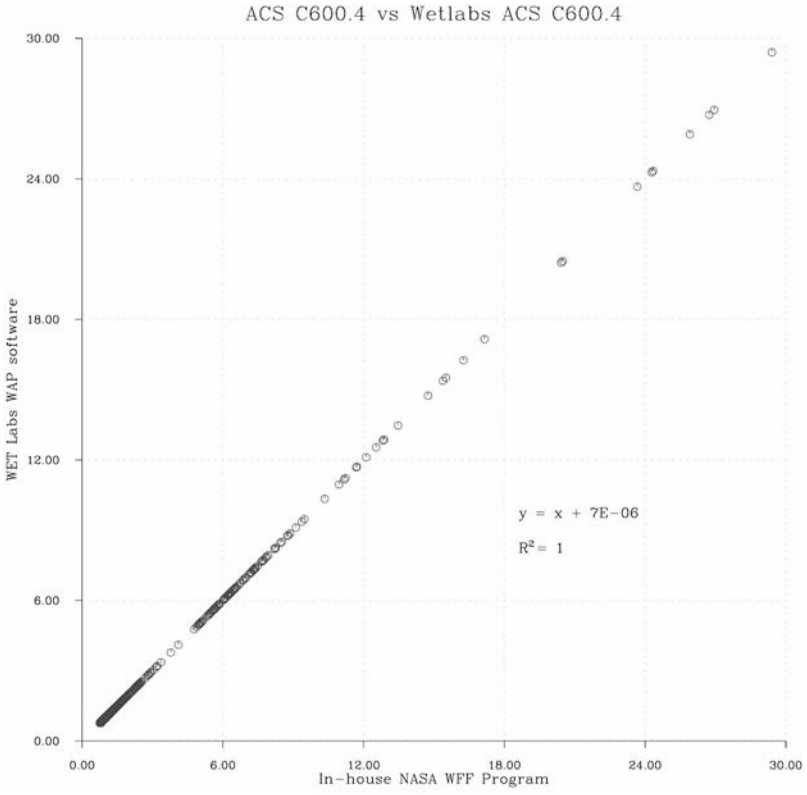


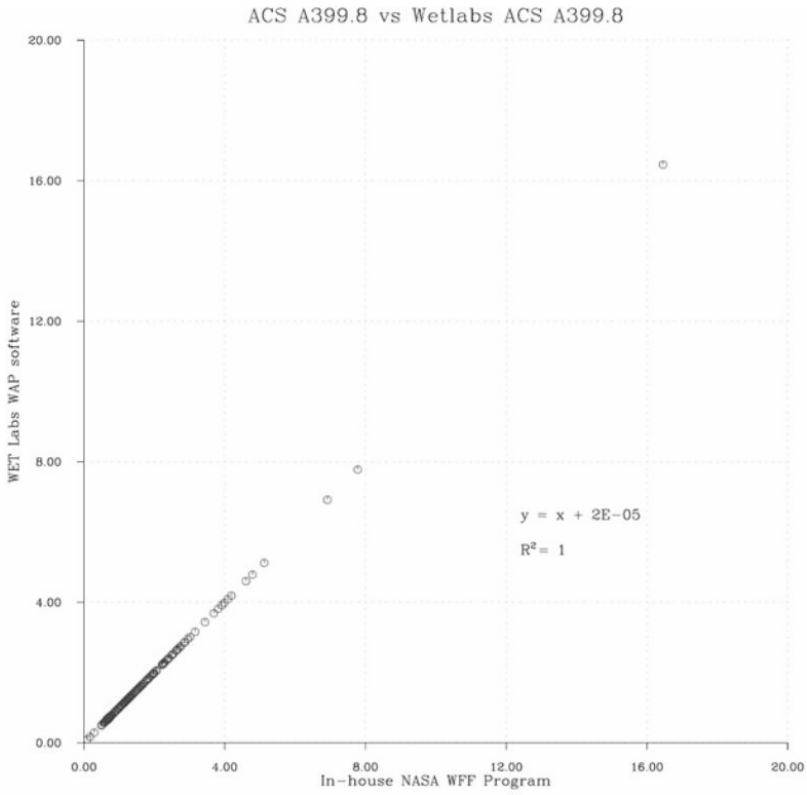

Plot 1 of AC-S differences
Word Minimum Maximum Range Color
X 1: 1 1199 1198
C400.7 : -0.00001000 0.00001000 0.00002000 blue
C600.4 : -0.00001000 0.00000000 0.00001000 red
A399.8 : -0.00003000 -0.00001000 0.00002000 green
A601.4 : 0.00000000 0.00001000 0.00001000 purple
0.000020
0.000010
0.000000
-0.000010
-0.000020
-0.000030
1
241
480
720
959
1199

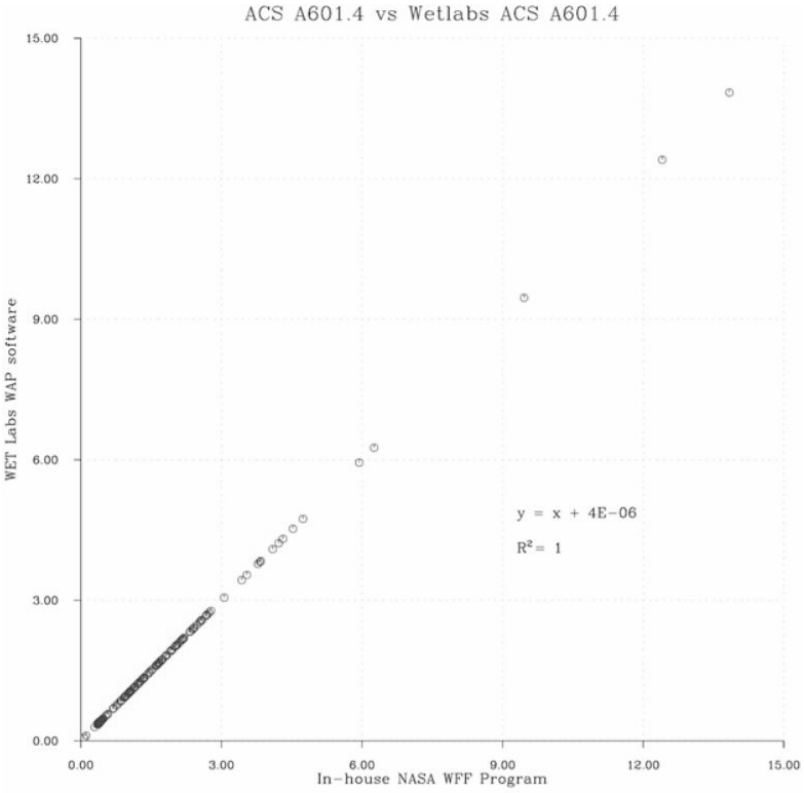

Plot 2 of AC-S differences
Word Minimum Maximum Range Color
X 1: 1 1199 1198
C400.7 : -0.00000700 0.00001500 0.00002200 blue
C600.4 : -0.00001200 -0.00000200 0.00001000 red
A399.8 : -0.00003000 -0.00001400 0.00001600 green
A601.4 : -0.00000100 0.00000900 0.00001000 purple
0.000020
0.000010
0.000000
-0.000010
-0.000020
-0.000030
1
241
480
720
959
1199

Appendix E
ACS vs Wetlabs




ACS C600.4 vs Wetlabs ACS C600.4
WET Labs WAP software
In-house NASA WFF Program
y = x + 7E-06
R² = 1
0.00
6.00
12.00
18.00
24.00
30.00


ACS A399.8 vs Wetlabs ACS A399.8
WET Labs WAP software
In-house NASA WFF Program
y = x + 2E-05
R² = 1
0.00
4.00
8.00
12.00
16.00
20.00


ACS A601.4 vs Wetlabs ACS A601.4
WET Labs WAP software
In-house NASA WFF Program
y = x + 4E-06
R² = 1
0.00
3.00
6.00
9.00
12.00
15.00

Abbreviations & Acronyms

a_t	Total absorption coefficient
a_w	Absorption coefficient of water
a_{ph}	Absorption coefficient of phytoplankton
a_d	Absorption coefficient of detritus
a_i	Absorption coefficient of inorganic matter
a_{CDOM}	Absorption coefficient of Chromophoric Dissolved Organic matter
a_{meas}	Measured absorption coefficient at *in situ* temperature
a_{tcorr}	Absorption coefficient corrected for changes in water temperature
a_{tscorr}	Absorption coefficient corrected for temperature and salinity effects
$a_{p,\ spectrophotometer}$	Particulate absorption coefficient measured by Perkin Elmer LS800 UV/VIS spectrophotometer
$a_{ac\text{-}s}$	Absorption coefficient of Milli-Q water offset
$a_{row,\ t,\ ac\text{-}s}$	Row data of total absorption coefficient by ac-s
$a_{t,\ ac\text{-}s}$	Total absorption coefficient corrected from temperature, salinity, and scattering effects with as-s measurement
ac-s	WET Labs absorption and attenuation meter at 83 distinct wavelengths from 390-750 nm
ac-9	WET Labs absorption and attenuation meter at 9 wavelengths from 412-715 nm
AOP	Apparent Optical properties
b_b	Backscattering coefficient
b_t	Total scattering coefficient
b_w	Scattering coefficient of water
b_{ph}	Scattering coefficient of phytoplankton
b_d	Scattering coefficient of detritus
BIOME	Bio-physical interactions in Ocean Margin Ecosystems
c_t	Total attenuation coefficient
c_{tcorr}	Attenuation coefficient corrected for changes in water temperature
c_{meas}	Measured attenuation coefficient at *in situ* temperature

c_{tscorr}	Attenuation coefficeint corrected for temperature and salinity effects
S_i	*In situ* salinity
$c_{ac\text{-}s}$	Attenuation coefficient of Milli-Q water offset
$c_{row,\ t,\ ac\text{-}s}$	Row data of total attenuation coefficient by ac-s
$c_{t,\ ac\text{-}s}$	Total attenuation coefficient corrected from temperature, salinity, and scattering effects with ac-s measurement
$c_{t,\ spectrophotometer}$	Total attenuation coefficient by spectrophotometric method by Magnuson *et al*. (2004)
CDOM	Chromophoric Dissolved Organic Matter
Chl *a*	Chlorophyll *a*
CTD	Conductivity Temperature Depth Profiler
G	Constant dependent on the angular distribution of the light field and the volume scattering function
GSFC	Goddard Space Flight Center
IOP	Inherent Optical Properties
ISUS	*In Situ* Ultraviolet Spectrophotometer
K_d	Diffuse attenuation coefficients for downwelling irradiance
LED	Light-Emitting Diode
NASA	National Aeronautics and Space Administration
POC	Particulate Organic Carbon
R_{rs}	Reflectance
T_i	*In situ* Temperature
T_{norm}	Temperature to which the absorption and attenuation coefficient are being normalized
VSF	Volume Scattering Function
WAP	WET Labs Archive File Processing
WFF	Wallops Flight Facility
WWW	World Wide Web
z	Depth
σ	Wavelength

ψ_t	Wavelength specific slope of temperature
$\psi_{s,a}$	Wavelength specific slope of salinity for absorption
$\psi_{s,c}$	Wavelength specific slope of salinity for attenuation

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14. ABSTRACT

Ocean color algorithms are based on the parameterization of apparent optical properties as a function of inherent optical properties. WET Labs underwater absorption and attenuation meters (ac-9 and ac-s) measure both the spectral beam attenuation [c (λ)] and absorption coefficient [a (λ)]. The ac-s reports in a continuous range of 390-750 nm with a band pass of 4 nm, totaling approximately 83 distinct wavelengths, while the ac-9 reports at 9 wavelengths. We performed the ac-s field measurements at nine stations in the Mid-Atlantic Bight from water calibrations to data analysis. Onboard the ship, the ac-s was calibrated daily using Milli Q-water. Corrections for the in situ temperature and salinity effects on optical properties of water were applied. Corrections for incomplete recovery of the scattered light in the ac-s absorption tube were performed. The fine scale of spectral and vertical distributions of c (λ) and a (λ) were described from the ac-s. The significant relationships between a (674) and that of spectrophotometric analysis and chlorophyll a concentration of discrete water samples were observed.

15. SUBJECT TERMS

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