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The calibration and validation of SeaWiFS data

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Abstract

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is the successor ocean color imaging system to the Nimbus-7 Coastal Zone Color Scanner (CZCS). The SeaWiFS calibration and validation effort includes spacecraft, atmospheric, sea surface, subsurface (or in situ), plus laboratory and data analysis components which require pre- and postlaunch activities. The most important goals of this effort are to produce water-leaving radiances with an uncertainty of 5% in clear-water regions and chlorophyll *a* concentrations within ±35% over the range of 0.05–50 mg m^{-3}. The first objective requires field instruments with a calibration and measurement capability on the order of 1%; because these challenging in situ measurements will be acquired from a variety of field instruments over the five-year mission interval, a measurement assurance program is required. This program consists of several activities: an accurate prelaunch characterization and calibration of the SeaWiFS instrument; a Marine Optical Buoy (MOBY) rotation in clear water to provide a water-leaving radiance time series for postlaunch vicarious calibration; the SeaWiFS Bio-Optical Archive and Storage System (SeaBASS) to hold the relevant data; clearly defined SeaWiFS Ocean Optics Protocols (SOOP) for established data collection methodologies; annual SeaWiFS Intercalibration Round-Robin Experiments (SIRREXs) for intercomparing field and calibration equipment, and training scientific personnel; direct comparison to a national standard laboratory using the SeaWiFS Transfer Radiometer (SXR); a portable field source, called the SeaWiFS Quality Monitor (SQM), for monitoring the temporal stability of the calibration of field instruments; a highly accurate atmospheric correction algorithm designed for the SeaWiFS instrument response functions; bio-optical algorithms that encompass a broad range of bio-optical provinces; and satellite data processing, quality control, and analysis procedures for monitoring the postlaunch performance of the sensor and the validity of the derived products. The culmination of many of these activities is the deployment of the instruments and methodologies on Atlantic Meridional Transect (AMT) cruises between England and the Falkland Islands, a 13 000 km voyage spanning more than 100° of latitude, with a calibration and measurement accuracy that is on the order of 1%. The AMT Program is the primary product validation activity supported by the SeaWiFS

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Project. The AMT cruises also serve as a testbed for new technology development and have demonstrated that high quality bio-optical data can be routinely provided to the Project in near-real time.

Contents

1. Introduction

Measurements from aircraft and ships in the 1960s and 1970s (Clarke, Ewing & Lorenzen, 1970; Kim, McClain, Blaine, Hart, Atkinson & Yoder, 1980), demonstrated satellites could be used to measure the spectra of sunlight reflected from ocean waters, and proved ocean color is a powerful tool for understanding biological and physical marine processes. For most of the world ocean, the radiance reflected in the visible part of the spectrum (400–700 nm) is related to the concentration of chlorophyll and other plant pigments. Chlorophyll is a green pigment, and the color of seawater changes from blue to green as the concentration of chlorophyll increases, so the amount of phytoplankton in ocean waters can be estimated if the concentration of chlorophyll is known. Consequently, satellite ocean color data can be used to determine the abundance of ocean biota on a global scale.

The Nimbus-7 Coastal Zone Color Scanner (CZCS) was launched by the National Aeronautics and Space Administration (NASA) in October 1978, and was the first satellite sensor designed specifically for estimating pigment concentrations in the ocean. The mission was designed as a proof-of-concept experiment with narrowly defined objectives, namely, a limit of two hours of coverage per day, a one-year demonstration lifetime, and a very modest 10% data processing goal for level-2 products derived from the level-1 calibrated radiances (Hovis et al., 1980; Hovis, 1981). The activities of the Nimbus Experiment Team (NET) are summarized by Acker (1994).

The CZCS mission was a scientific success (Barale & Schlittenhardt, 1993) and provided many lessons to the science community regarding the performance of an ocean color remote sensing system, including requirements for calibration, validation, atmospheric corrections, bio-optical algorithms, data processing, and data access. Despite the successes, however, much of the CZCS data remain unverified and inadequately calibrated (Evans & Gordon, 1994). The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is the NASA successor instrument to the CZCS. From the inception of the SeaWiFS Project, a substantial fraction of Project resources have been committed to calibration and validation activities, and a great emphasis was placed on the documentation of all Project-related activities through the *SeaWiFS Technical Report Series* and Project web pages. Finally, the NASA Biogeochemistry Program and the Project jointly support the development of the SeaWiFS Data Analysis System (SeaDAS), which has been distributed to more than 500 unique sites (Fu, Schieber, Settle, Darzi, McClain & Arrigo, 1996).

The SeaWiFS instrument was launched 1 August 1997 on board the OrbView-2 (formerly SeaStar) spacecraft. Unlike Nimbus-7, which carried nine scientific payloads, OrbView-2 only carries the SeaWiFS instrument. SeaWiFS became operational on 18 September 1997 and routinely provides global coverage every two days. It is the second in sequence of ocean color missions which began with the recently failed Japanese Advanced Earth Observation Satellite (ADEOS), which operated from August 1996 to June 1997 and carried the Ocean Color and Temperature Scanner (OCTS) and the Polarization and Directionality of the Earth's Reflectance (POLDER) instrument. ADEOS and SeaWiFS will be followed by other global missions such as the NASA Earth Observing Satellite (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS), the European Medium Resolution Imaging Spectrometer (MERIS), and the Japanese Global Imager (GLI). The characteristics of many of these sensors are summarized in Morel (1998).

With the SeaWiFS instrument operational, a continuous global time series of ocean color data has been initiated that should extend into the next century. Because SeaWiFS has a design lifetime of five years, it is likely to be operational when MODIS and MERIS are launched. Although the data coverage advantages — both satellite and in situ — from multiple satellite missions are substantial (Gregg et al., 1998), a combined data set will only be useful for quantifying long-term trends in oceanic biological processes if comprehensive and consistent calibration and validation activities are available for each mission. These activities must include product and calibration comparisons when missions overlap in time, since the instruments will not be identical (in terms of their radiometric characteristics), and the derived products from each will be based on sensor-specific algorithms. Consequently, care must be taken to ensure that the algorithms, both atmospheric and bio-optical, produce similar derived products. The intercalibration and validation of these data sets is the objective of the international Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) program (Mueller, McClain, Caffrey & Feldman, 1998). The NASA part of the SIMBIOS activity is co-located with the SeaWiFS Project to help ensure the techniques developed for instrument calibration and algorithm development for SeaWiFS will provide a baseline for subsequent ocean color missions.

The optical and pigment measurements from the Atlantic Meridional Transect (AMT) Program figure prominently in both the SeaWiFS and SIMBIOS validation efforts. The AMT Program exploits the passage of the Royal Research Ship (RRS) *James Clark Ross* (JCR) as it transects the Atlantic Ocean between Grimsby (UK) and Port Stanley (Falkland Islands) with a port call in Montevideo (Uruguay). In September, the JCR sails from the UK, and the following April it makes the return trip. The AMT Program collects scientific data from approximately 50°N to 50°S with a primary objective to investigate physical and biological processes, as well as to measure the meso- to basin-scale bio-optical properties of the Atlantic Ocean. The calibration and validation of remotely sensed observations of ocean color is an inherent objective of these studies: first, by relating in situ measurements of water-leaving radiance to satellite measurements, and second, by measuring the bio-optically active constituents of the water.

2. SeaWiFS calibration and validation

The purposes of the SeaWiFS Project are to obtain valid ocean color data of the world ocean for a five-year period, to process the data in conjunction with ancillary data to meaningful biological parameters, and to make the data readily available to researchers (Hooker & Esaias, 1993). Unlike CZCS, which required data from its entire lifetime to produce one global image (partially incomplete over the southern

Pacific), the SeaWiFS instrument routinely produces global geophysical fields in near-real time. Inherent in any space flight mission for scientific applications are project functions to ensure a successful mission. The SeaWiFS Project is divided into three elements: Project Management, Data Management (including data capture, data processing, and mission operations), and Calibration and Validation. Although all of these elements are equally important to the success of the mission, the responsibilities and activities of the latter are the main interest here; details concerning the other elements can be found in Hooker, Esaias, Feldman, Gregg and McClain (1992).

The success of the SeaWiFS mission will be determined by the quality of the ocean color data set and its availability. The Calibration and Validation Element (CVE) is responsible for the former which involves characterizing and calibrating the SeaWiFS system; supporting the development and validation of algorithms for bio-optical properties and atmospheric correction; analyzing trends and anomalies in the derived products and sensor performance; selecting ancillary data sets that are used in data processing (e.g., winds, ozone, and atmospheric pressure); and verifying the processing code. The culmination of properly executing these responsibilities is achieving a radiometric accuracy to within 5% absolute and 1% relative, water-leaving radiances to within 5% absolute, and chlorophyll *a* concentration (C_a) to within 35% over a range of 0.05–50.0 mg m^{-3}. The initial strategy for the CVE is presented in McClain et al. (1992).

Achieving the accuracy goals is an ongoing and continuously monitored activity. The SeaWiFS data processing system is designed to handle simultaneous routine operations and episodic data reprocessings as deemed necessary by the Project and the scientific community. Reprocessings are the result of refinements in the navigation, calibration, atmospheric correction, and bio-optical algorithms which result in significant improvements in the derived products. The CVE, working with the science community, is responsible for identifying problems and solutions, for documenting the improvements, and for integrating the modifications into the operational processing code. To date, reprocessings have been executed in February and August 1998.

The diversity of the calibration and validation requirements suggests a variety of organizational schemes for executing the tasks involved. The formalism adopted in the Project was derived from the equation governing the basic SeaWiFS measurement, that is, the radiative transfer equation for the radiance observed in orbit:

$$L_T(\lambda) = L_r(\lambda) + L_a(\lambda) + L_{ra}(\lambda) + TL_g(\lambda) + t(L_f(\lambda) + L_W(\lambda)), \quad (1)$$

where $L_T(\lambda)$ is the total radiance at the top of the atmosphere, which is composed of radiance contributions from the multiple scattering of air molecules (Rayleigh scattering), $L_r(\lambda)$; multiple scattering by aerosols in the absence of air, $L_a(\lambda)$; interactions between air molecules and aerosols, $L_{ra}(\lambda)$; reflections from glint and foam, $TL_g(\lambda)$ and $tL_f(\lambda)$, respectively (the coefficient T is the direct solar transmittance and t is the diffuse atmospheric transmittance); and backscattering out of the water resulting from subsurface interactions, $tL_W(\lambda)$. The terms in Eq. (1) can be grouped into simpler interaction terms:

$$L_T = L_{\mathrm{atm}} + L_{\mathrm{sfc}} + L_{\mathrm{sub}}, \quad (2)$$

where L_{atm} is the contribution from the atmospheric interactions, $L_r(\lambda) + L_a(\lambda) + L_{ra}(\lambda)$; L_{sfc} is the contribution from surface reflections, $TL_g(\lambda) + tL_f(\lambda)$; and L_{sub} is the contribution from subsurface interactions, $tL_W(\lambda)$. The formulation given in Eq. (2) divides the calibration and validation issues into three components: spacecraft (L_T), atmospheric ($L_{\mathrm{atm}} + L_{\mathrm{sfc}}$), and in situ or subsurface (L_{sub}). The extraterrestrial solar irradiance can be used to express Eqs. (1) and (2) in terms of reflectances by applying the definition of reflectance. This alternative formulation is not adopted here, because the emphasis within the field program is to make radiance, rather than reflectance, measurements.

A fourth component, the laboratory and analysis component, arises from Eq. (2) once the diverse contributions from the individual groups have been defined. Put simply, the data and collection procedures for each group have to be defined and accepted by the Project. Once the data are acquired, they have to be incorporated into a processing methodology, so they a) contribute to the agreed upon objectives, and b) ensure consistency and traceability when combined in the total radiance balance Eq. (1), so they can be used in other radiometric relationships (e.g., bio-optical algorithms). Consequently, the laboratory and analysis component addresses measurement issues common to all groups, data processing and analysis methodologies, and product generation and evaluation.

The CVE is responsible for ensuring the activities associated with all components are well coordinated and contribute towards a processing system that delivers timely products in keeping with SeaWiFS accuracy goals. Whenever the staff or expertise are inadequate to address any of the issues associated with meeting the mission objectives, the Project relies on close working relationships and collaborative agreements with the scientific community. To accomplish this, the CVE has made every effort possible to develop a staff with the necessary skills to collaborate with these external communities and correctly use the scientific results and technologies required for executing their responsibilities. The prelaunch CVE is documented in McClain et al. (1996) and has remained basically the same since launch.

3. The laboratory and analysis component

This component is not associated with just one of the primary radiometric components, but contributes to aspects of each. When the SeaWiFS Project was formally initiated in 1990, less than two years after the formation of the MODIS Oceans Team, there was no coordination in the marine bio-optics community designed to support an ocean color satellite mission. Through consultation with members of the community, a number of activities were initiated for developing the necessary infrastructure within the community required for meeting SeaWiFS Project objectives.

3.1. Prelaunch laboratory and analysis activities

The prelaunch activities for this component were as follows:

1. Establish the optical protocols for data collection and analysis, and support topical workshops as needed (e.g., an absorption measurement workshop);

2. Organize and execute SeaWiFS Intercalibration Round-Robin Experiments (SIRREXs) to provide for annual intercalibrations of calibration equipment and in situ instruments;
3. Design and produce new instrumentation required by the CVE to meet its data quality objectives, e.g., the SeaWiFS Transfer Radiometer (SXR) and the SeaWiFS Quality Monitor (SQM);
4. Create the SeaWiFS Bio-Optical Archive and Storage System (SeaBASS) to retain the bio-optical data required by the Project;
5. Formulate and test the bio-optical algorithms in collaboration with the bio-optics working group as reported in Volumes 18, 24, 36 and 43 of the *SeaWiFS Technical Report Series* (Firestone & Hooker, 1995a,b, 1996, and 1998 respectively);
6. Support bio-optical Data Analysis Round-Robin (DARR) workshops;
7. Develop methodologies for the evaluation and quality control of SeaWiFS data (McClain et al., 1996); and
8. Verify all operational level conversion software and document the processing flow (Darzi, 1998).

A prelaunch support activity for the laboratory and analysis component was to assist in the development of a simplified version of the operational processing system, SeaDAS, which could be distributed to the user community (Fu et al., 1996). SeaDAS is primarily supported by the NASA Biogeochemistry Program, but would not be possible without a close working relationship between the SeaDAS team and CVE staff who have a detailed understanding of the processing codes incorporated into SeaDAS.

3.1.1. Optical protocols

If the primary SeaWiFS goals of 5% accuracy in water-leaving radiance and 35% accuracy in C_a are to be met, or even closely approached, it is imperative that the supporting measurements meet a uniform standard of quality and accuracy. To that end, the SeaWiFS Project convened a workshop to draft the SeaWiFS Ocean Optics Protocols (SOOP) which would adhere to the Joint Global Ocean Flux Study (JGOFS) sampling procedures (Joint Global Ocean Flux Study, 1991) and define the standards for optical measurements to be used in SeaWiFS radiometric validation and algorithm development (Mueller & Austin, 1992). The key objective of the workshop was to recommend protocols and standards for supporting in situ optical measurements and define the following:

1. The required optical parameters for validating SeaWiFS atmospheric correction algorithms and normalized water-leaving radiances, $L_{WN}(\lambda)$, and for monitoring the calibration and stability of the satellite sensor;
2. The instrumentation requirements and standards for measuring these variables, including definitions of measured quantities, wavelengths, sensitivity, accuracy and stability, field of view, and band specifications;
3. The optical instrument characterization, intercalibration standards, and related protocols, including a) laboratory calibration and characterization measurements,

accuracies, and procedures to be applied to instruments used in SeaWiFS validation and algorithm development activities; b) pre- and post-deployment measurements and procedures to be followed with moored instrumentation; and c) procedures for instrument calibration and characterization along with the requirements for record keeping, traceability, and intercalibrations of radiometric and optical standards between participating laboratories;
4. The at-sea optical sampling strategy and protocols, including such considerations as a) the rationale and justifications for moored, underway, drifting, shipboard, and airborne measurements; b) depth resolution in optical profiles, total sampling depths, ship shadow avoidance, and instrument self-shadowing effects; and c) time of day, sky conditions, season, and geographic considerations;
5. The analytical approaches to be used, including the procedures and methods for generating variables from the in situ observations, e.g., $L_{WN}(\lambda)$, remote sensing reflectance $R_{\mathrm{rs}}(\lambda)$, etc., and uncertainty analyses;
6. The protocols for ancillary measurements, data archiving, database population, and data access; and
7. The atmospheric measurements and the degree to which standard methodologies are available.

The SOOP are periodically being updated as deficiencies are identified (Mueller & Austin, 1995). Examples of immature protocols are those for turbid water and above-surface measurements (including those made from aircraft).

3.1.2. Instrument intercalibrations

The SIRREX activity is a direct consequence of the need to ensure entries into the optical database are of a uniform quality and are internally consistent to within a precision of 5%. The CVE supported the first five SIRREXs; subsequent round-robins will be supported by the SIMBIOS program, because the CVE has a limited budget. The objectives of the SIRREX activity, singularly and over time, are to do the following:

1. Intercalibrate FEL lamp working standards of spectral irradiance and to reference each to the National Institute of Standards and Technology (NIST) scale of spectral irradiance via a secondary standard;
2. Intercalibrate the integrating sphere sources of spectral radiance;
3. Intercompare the plaques used to transfer the scale of spectral irradiance from an FEL lamp to a scale of spectral radiance, as well as the support electronics involved (most critically shunts and voltmeters);
4. Evaluate the suitability of the equipment and laboratory methods being employed for radiometric calibrations at each institution; and
5. Intercompare radiometers in the field while evaluating the measurement protocols being used.

In the progress from the first to the third SIRREX, which were all held at the Center for Hydro-Optics and Remote Sensing (CHORS), uncertainties in the traceability to

NIST of intercomparisons between the spectral irradiance of lamps improved from 8% to 2% to 1% (Mueller, 1993; Mueller et al., 1994; Mueller, Johnson, Cromer, Hooker, McLean & Biggar, 1996, respectively). Intercomparisons of sphere radiance showed little improvement between SIRREX-1 and SIRREX-2, with uncertainties as large as 7% in both experiments. In SIRREX-3, however, a more rigorous characterization of both spheres and transfer radiometers reduced the uncertainties to approximately 1.5% in absolute spectral radiance and 0.3% in radiance stability for most spheres (inadequate lamp current regulation was the primary source of larger uncertainties). Shunts and voltmeters were intercompared during the first three SIRREXs, and in general, the equipment used by all participants met the specified levels of uncertainty.

Plaque reflectance measurements in SIRREX-3 represented a qualitative improvement over results obtained during earlier SIRREXs, primarily because of improved SXR performance. Significant improvements are needed in this technique, however, if several poorly quantified uncertainties are to be resolved, including the development of proper methods for stray light baffling, goniometric corrections for FEL off-axis irradiances, and quantitative characterization of the bidirectional reflectance distribution function (BRDF) of Spectralon™ plaques.

In addition to plaque concerns, SIRREX-3 demonstrated the need for rigorous laboratory practices. The shift in spectral irradiance of a lamp emphasized the need to closely adhere to several important protocols for lamp usage and record keeping in general, and with NIST secondary standards in particular (i.e., lamp operating hours should always be recorded). The voltage across the lamp terminals, as well as the lamp operating current, should be measured and recorded each time a lamp is used. As a matter of routine practice, the irradiance of a NIST secondary standard of spectral irradiance should be transferred locally to several additional working standard FEL lamps, and the transfer periodically verified for each of the local working standards at intervals of 20–30 lamp hours.

Given the repeated failures in laboratory technique during the first three SIRREXs, the primary recommendation from SIRREX-3 was: … *an emphasis on training and work to foster and encourage uniform use of accepted protocols for laboratory calibration of radiometric instruments*. This was the starting point for SIRREX-4 (Johnson et al., 1996) which was held at NIST during 3–10 May 1995. The idea was to host the activity in a setting where proper technique could be discussed and demonstrated. Each day was split between morning lectures and afternoon laboratory sessions or "practicals". The former gave the attendees a chance to present what was important to them and discuss it with acknowledged experts in radiometry, while the latter presented a unique opportunity for training and evaluation in the presence of these same experts. There were five laboratory sessions, which were concerned with: 1) determining the responsivity of a spectroradiometer and the spectral radiance of an unknown integrating sphere source, 2) demonstrating spectral field calibration procedures for an integrating sphere using three different instruments, 3) measuring spectral radiance using the plaque method, 4) setting up and aligning lamp calibration transfer standards using NIST specifications for irradiance measurements, and 5) characterizing radiometric instruments.

SIRREX-5 was also held at NIST on 23–30 July 1996 and was the first time instrument intercomparisons were performed at field sites near NIST (Johnson, Yoon, Early, Thompson, Hooker, Eplee et al., 1999a). The goals were to continue the emphasis on training and the implementation of uniform measurement practices, investigate the calibration methods in use by the scientific community, provide discussion opportunities, demonstrate new technology (the SQM), and intercompare selected field instruments. Daily lectures in the morning and practicals in the afternoon dealt with: 1) measuring in-water and in-air radiant flux, 2) using the plaque method for measuring spectral radiance responsivity, 3) testing portable sources as calibration devices or stability monitors, and 4) participating in various ancillary exercises designed to illustrate radiometric concepts.

3.1.3. New instrumentation

One of the original concepts to be tested in the SIRREX activity was to verify the sources and calibration set-up procedures at individual calibration facilities for both spacecraft and in situ instruments. To do so required an accurate, stable, and portable radiometer, a so-called transfer radiometer, designed specifically for SeaWiFS calibration applications. The SXR was designed and built by the Optical Technology Division at NIST in collaboration with the SeaWiFS Project. It is a six-channel radiometer calibrated for spectral radiance over the (approximate) wavelength range of 400–800 nm (Johnson, Fowler & Cromer, 1998a). Each channel consists of a temperature-stabilized silicon detector, a narrow bandpass interference filter, and a precision current-to-voltage amplifier. The 2.4° full-angle field-of-view aperture is imaged onto the six detectors, and can be bore-sight focused from approximately 0.85 m to infinity. The SXR has been used at SIRREX-2 through SIRREX-4, the Marine Optical Buoy (MOBY) support facility in Honolulu (Hawaii), and at Nippon Electric Corporation in Yokohama (Japan) during an OCTS integrating sphere comparison (Johnson, Sakuma, Butler, Biggar, Cooper, Ishida et al., 1997). It has proved to be a reliable transfer radiometer, with an uncertainty in radiance repeatability of less than 0.1% and an estimated uncertainty of approximately 1.5% in radiance responsivity at all wavelengths.

Another instrumentation need that was identified early in the activities of the CVE was for a portable source that would allow routine stability checks between radiometer calibrations in the field. Instrumental drift from filter deterioration and transportation stresses, which can cause shifts in the radiometric response of a device, must be tracked. Because no commercial device was available, the SeaWiFS Project teamed with the NIST Optical Technology Division to produce one. The engineering design and characteristics of the SQM are described by Johnson, Shaw, Hooker and Lynch (1998b), so only a brief description is given here. Two different lamp sets, with eight bulbs in each set, allows for three flux levels. The exit aperture of the SQM is large, homogeneous in radiance, and was designed to approximate a lambertian radiator. An internal heater provides operational stability and decreased warm-up intervals. Internal temperature-controlled silicon photodiodes with colored glass filters monitor the stability of the generated light field. The internal monitors normalize the flux of the source, so the actual change in the responsivity of the field sensor can be determined. A change in the latter is distinguished from a change in the internal detectors through the use of three reference devices, or fiducials. The front surface of each fiducial is protected when not in use, so its reflectivity and loading on the exit aperture does not change over time. A kinematically designed D-shaped collar is used to ensure all devices being tested view the same part of the SQM aperture each time they are used.

The SQM field commissioning on the AMT-3 cruise demonstrated the following (Hooker & Aiken, 1998):

1. The stability of field radiometers can be monitored at less than the 1% level, in terms of the radiometric response of the sensors;
2. The light field is sufficiently stable to model changes in the radiometric detectors;
3. Daily SQM sessions are required to resolve short-term temporal changes of the radiometers; and
4. SQM performance degrades approximately 0.6% over the course of a 36-day deployment.

The SQM is now an integral component for quantifying the stability of field radiometers and has been used on all AMT cruises since its commissioning. The SIMBIOS Project provided initial funding for the commercialization of the original SQM design which resulted in two new instruments: the SQM-II manufactured by Satlantic, Inc. (Halifax, Canada), and the SQM-100 manufactured by Yankee Environmental Systems, Inc. (Turners Falls, Massachusetts).

3.1.4. Bio-optical database

Development of global or regional bio-optical algorithms requires a data set from the widest variety of bio-optical provinces possible. In addition, independent data for postlaunch validation of the derived diffuse attenuation coefficient (K), pigment concentrations, and L_W values, plus any other future products, are required. When the SeaWiFS Project began, the only data sets available with sufficient quality for algorithm evaluation were the NET data sets for pigment and $K(490)$, the former having only 53 points from coastal US stations. Clearly, a dedicated archive for such data was needed. The only economically feasible approach was to maximize data acquisition by soliciting contributions of data from the oceanographic community at large, and to combine them with data collected from field programs and instrument calibrations (SIRREX activities) in an easily accessed database.

The acquisition of the historical and contemporary data sets requires the implementation of QC, documentation, and cataloging procedures, plus the design of a database structure suitable for bio-optical data with a user-friendly interface. SeaBASS serves as a repository for numerous data sets of interest to the SeaWiFS Science Team and other approved investigators in the scientific community (Hooker, McClain, Firestone, Westphal, Yeh & Ge, 1994). The data collected include results from SIRREX activities; prelaunch characterization of the SeaWiFS instrument; the AMT Program, California Cooperative Fisheries Institute (CalCOFI) campaigns, and Marine Optical Characterization Experiment (MOCE) cruises; Plymouth Marine Bio-

Optical Data Buoy (PlyMBODy) and MOBY deployments; time series collected at the Bermuda Atlantic Time-Series Station (BATS) and the Acqua Alta Oceanographic Tower (AAOT); and a large number of other bio-optical data sets in accordance with the SOOP. The primary goal of the archive is to provide a simple mechanism for querying the available archive and requesting specific items, while assuring that the data are made available only to authorized users.

The SeaBASS data set began with historical data (Firestone & McClain, 1994) contributed by members of the SeaWiFS Science Team for CZCS (Arrigo & McClain, 1995) and SeaWiFS postlaunch validation purposes. The pigment data set has continued to grow, station locations for which are shown in Fig. 1. Note the poor sampling in the southern Indian Ocean and the South Atlantic Ocean. The number of observations suitable for SeaWiFS algorithm development is limited because of the specific suite of simultaneous pigment and optical observations, SeaWiFS bands, and the radiometric accuracies required. Unfortunately, most subsurface data in the near-infrared are questionable because of instrument self-shading, as indicated by recent theoretical studies (Gordon & Ding, 1992). SeaBASS is being continually expanded as a joint effort between the SeaWiFS and SIMBIOS projects.

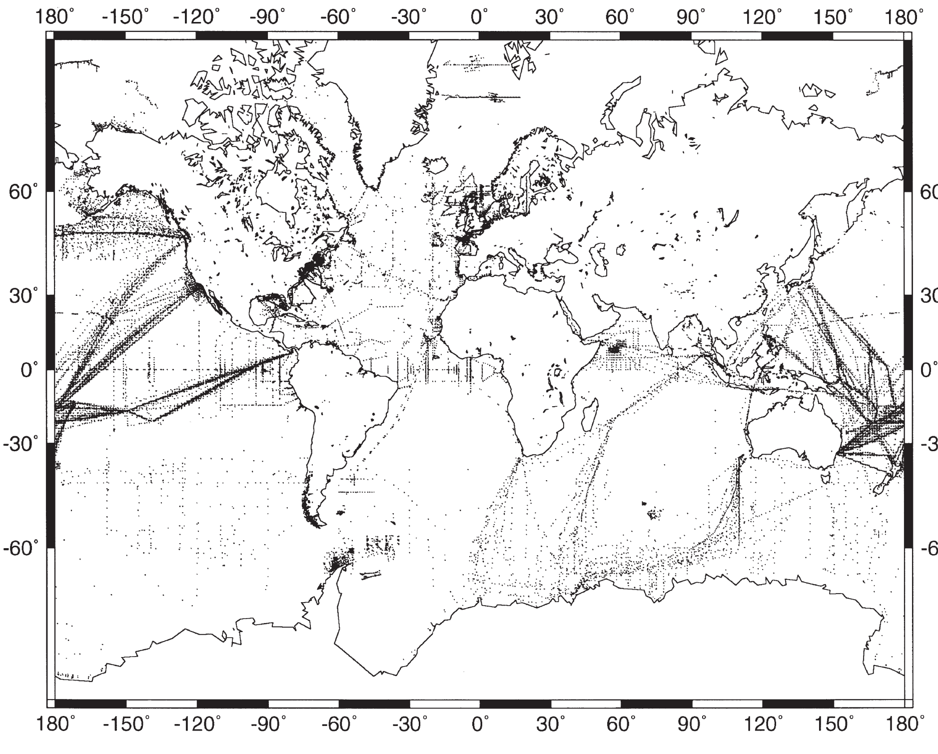


Fig. 1. The station locations for the historical pigment data set.

3.1.5. Bio-optical algorithms

Formulating the bio-optical algorithms begins with SeaBASS. These data will be accessible by Project-approved investigators for the development of advanced bio-optical and atmospheric correction algorithms. These investigators include not only members of the field teams, but others who contribute data of comparable quality, and investigators selected by the Project to work on bio-optical algorithms. The data protocols regarding rights, access, and distribution have been agreed upon (Hooker, Esaias & Rexrode, 1993a). The Project desires to promote new methodologies and will support an in-house capability to independently review, implement, and compare methodologies proposed by the research community, as discussed in McClain et al. (1992). This requires a detailed knowledge of the data sets, data preprocessing procedures, and relevant radiative transfer theory. The data processing required for these analyses will be performed separately from the routine SeaWiFS data processing.

To establish the review capability, several methods, developed primarily for CZCS data, have been compared by the CVE as a series of case studies (e.g., McClain et al., 1994). In terms of bio-optical algorithms, this includes four pigment concentration algorithms: the standard two-channel switching algorithm (Gordon, Clark, Brown, Brown, Evans & Broenkow, 1983), an iterative algorithm (Smith & Wilson, 1981), a three-channel algorithm (Muller-Karger, McClain, Sambrotto & Ray, 1990), and a European community algorithm developed for reprocessing CZCS data (Andersen, 1991; Sturm, 1993). The Bio-Optical Algorithm Subgroup of the SeaWiFS Science Team is tasked with delivering the operational algorithms, e.g., the $K(490)$ algorithm (Mueller & Trees, 1997). Nine working group meetings have been held to review the progress on the development of the operational algorithms and measurement protocols including a laboratory workshop at Scripps Institute of Oceanography on absorption measurement methodologies [see Firestone & Hooker (1998) for a meeting index].

3.1.6. Data analysis workshops

The accurate determination of upper-ocean apparent optical properties (AOPs) is essential for the vicarious calibration of the SeaWiFS instrument and the validation of the derived data products. To evaluate the effect analysis methods have on derived AOPs, the first DARR (DARR-94) workshop was sponsored by the SeaWiFS Project during 21–23 July 1994 (Siegel et al., 1995). Different methodologies from four research groups were applied to 10 spectroradiometry casts to evaluate how data analysis methods influence AOP estimation, and whether any general improvements can be made. The DARR-94 results did not show a clear preference among the data analysis methods evaluated. They did show, however, that some degree of 'outlier' rejection is required in order to estimate accurately upwelled radiance or downwelled irradiance immediately below the sea surface, $L_u(0^-, \lambda)$ and $E_d(0^-, \lambda)$, respectively.

Discussions on the operational algorithms at the bio-optics meetings indicated viable global algorithms for chlorophyll *a* and CZCS pigment could not be produced without a large database containing coincident in situ chlorophyll, $L_u(0, \lambda)$, and $R_{rs}(\lambda)$ measurements to evaluate the accuracy, precision, and suitability of a wide variety of ocean color chlorophyll algorithms being proposed for use by the Project. Consequently, the CVE initiated the development of such a database from the SeaBASS archive. These data sets consisted mostly of profile data and had to be quality controlled and processed to the derived products. A similar activity had been initiated elsewhere, so the final data set was a collaborative effort. The prelaunch algorithm development and evaluation process culminated with the SeaWiFS Bio-Optical Algorithm Mini-Workshop (SeaBAM). SeaBAM was designed to be an interactive data analysis workshop similar to DARR-94 with the expressed purpose of resolving discrepancies in the evaluation data set and selecting operational chlorophyll a and CZCS pigment algorithms to remove inconsistencies between the two leading candidate algorithms [see the SeaBAM summary in Firestone & Hooker (1998)].

The initial SeaBAM data set was composed of 919 stations encompassing chlorophyll concentrations from 0.019–32.79 mg m^{-3} and is archived in SeaBASS. Most of the observations are from Case-1 waters and approximately 20 observations are from Case-2 waters. A variety of statistical and graphical criteria were used to evaluate the performance of 2 semi-analytical and 15 empirical chlorophyll algorithms (O'Reilly, Maritorena, Mitchell, Siegel, Carder, Garver et al., 1998):

1. In general, the empirical algorithms performed better than the semi-analytical algorithms;
2. Cubic polynomial formulations were generally superior to other kinds of equations;
3. Empirical algorithms with increasing complexity (number of coefficients and wavebands), calibrated to the SeaBAM data set, were devised and evaluated to illustrate the relative merits of different formulations;
4. A modified cubic polynomial function, the so-called ocean chlorophyll 2 (OC2) algorithm, which uses $R_{rs}(490)/R_{rs}(555)$ was chosen as the at-launch SeaWiFS operational chlorophyll *a* algorithm; and
5. Improved performance was obtained using the ocean chlorophyll 4 (OC4) maximum band ratio wherein the ratio used is the greatest of $R_{rs}(443)/R_{rs}(555)$, $R_{rs}(490)/R_{rs}(555)$, or $R_{rs}(510)/R_{rs}(555)$.

The SeaBAM participants decided the operational algorithms should be based on the SeaBAM data set rather than using it to evaluate proposed algorithms based on more limited data sets. While OC4 performed best, concerns about possible artifacts in the pigment retrievals from band-ratio transitions, led the group to select OC2; OC4 would be evaluated using SeaWiFS data before it would be considered for operational processing.

3.1.7. Quality control

The QC procedures are based on the CZCS system (McClain, Feldman & Esaias, 1993) and include the review of level-1 through level-3 products, as well as the input fields used in the derivation of level-2 products (McClain et al., 1996). One major difference is that the only ancillary data fields used in the CZCS processing were historical ozone concentrations derived from the Nimbus Total Ozone Mapping Spectrometer (TOMS) while SeaWiFS requires ozone and three other ancillary data received in near-real time: surface winds, pressure, and relative humidity. The 3-hourly surface data sets are being received operationally in near-real time from the National Center for Environmental Prediction (NCEP). Daily ozone distributions are obtained from the Earth Probe TOMS within 2–3 days, with data from the TIROS Operational Vertical Sounder (TOVS) being used as a secondary source. All ancillary fields are converted to the hierarchical data format (HDF) and are passed through automated statistical checks and visual inspection (Darzi, Patt, Firestone, Schieber & McClain, 1994).

The EOS program worked closely with the SeaWiFS Project in implementing and testing HDF products, as well as the associated libraries, by providing a full-time programmer co-located with the Project. This collaboration greatly accelerated the development process. Space and time gaps in the data are filled either by interpolation or nearest neighbor substitution depending on the size or duration of the gap. The level-1 and level-2 products include metadata identifying the ancillary data required for the level-2 processing. The ancillary data are also distributed to the Goddard Space Flight Center (GSFC) Distributed Active Archive Center (DAAC).

Quality control also includes verification of the processing code, which is particularly important when many of the conversion routines are provided by other groups. For SeaWiFS, the University of Miami provided the level-2, and level-3 codes. All level-1 through level-3 processing codes were reviewed, tested, and documented (Darzi, 1998). This was a particularly challenging task, because it involved thousands of lines of code and the logic of many complex algorithms (calibration, atmospheric correction, masks and flags, bio-optical, binning, etc.). It also required close coordination between the CVE and the University of Miami to ensure corrections were properly implemented and that each group synchronized the updating of their code.

Instrument telemetry (e.g., focal plane temperatures) includes 34 parameters (McClain, Evans, Brown & Darzi, 1995) which are routinely monitored as a QC time series. This is also true of the spacecraft telemetry, which has produced immediate improvements to the remotely sensed data. By fine tuning the attitude control sensor alignments, gain settings, and other system variables, for example, the navigation was improved to within 1 pixel, from initial errors of over 40 pixels, within three months of operational data collection.

3.1.8. Operational products

The derived level-2 products fall into two categories, baseline or archive products, and potential evaluation SeaWiFS products (e.g., primary productivity). The initial set of level-2 archive products [L_{WN}(412, 443, 490; 510, 555), L_a(765, 865), τ_a(865), and ε(765, 865)] included 16 QC masks and flags (McClain et al., 1995) designed to optimize the quality of the pigment values. Evaluation products (e.g., pigments generated using alternative algorithms) are routinely generated as level-2 test products, but are only temporarily stored; they are not binned and distributed by the GSFC DAAC, but are made available to specific groups who requested them. Differentiation is made between CZCS-type pigment and SeaWiFS chlorophyll *a* concentrations, because the former is the summation of chlorophyll *a* and phaeophytin concentrations. The level-3 products are space/time average fields binned onto a standard 9 km grid so as to be comparable to sea surface temperature fields being produced by the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder project.

Campbell, Blaisdell and Darzi (1995) proposed the initial binning algorithm using a maximum likelihood estimator of the mean value, but it was found during prelaunch testing using simulated data (Gregg, Patt & Woodward, 1994) to be unstable when the variance was high, so standard mean values are being used. Indeed, the routine processing of simulated data proved invaluable in debugging the operational processing code and QC procedures. All archive products, satellite and ancillary data, are produced as HDF files. The CVE has assumed the responsibility of defining and maintaining the HDF product specifications, which are posted on the Calibration and Validation web page, and for the development of the product generation routines.

3.2. Postlaunch laboratory and analysis activities

The postlaunch laboratory and analysis activities are concerned with either maintaining or extending the prelaunch activities. For example, changes in the operational derived product algorithms, including the QC masks and flags, and requirements for new derived products, are inevitable. In addition, changes will be suggested as more is learned about bio-optics, atmospheric corrections, and processing procedures during the course of the mission. Procedures have, therefore, been agreed upon for modifying, implementing, and adding new algorithms or products to ensure this needed evolution can take place. In particular, the scope of effort and tasking for the data processing group within the Project supports both routine real time and biannual data reprocessing scenarios.

Much of the first 90 days of operation, the contractual acceptance period, was spent verifying that the data met all the acceptance criteria (Table 1). Some radiometric criteria could only be evaluated in the prelaunch data (Barnes, Barnes, Esaias & McClain, 1994a; Barnes, Holmes, Barnes, Esaias, McClain & Svitek, 1994b), but others could be examined using solar (the signal-to-noise ratio and the short-term stability), lunar (the modulation transfer) and local area coverage (LAC) high resolution scenes (a Bahamas Banks–Tongue of the Ocean scene for bright target recovery). Dark current data at the beginning of each scan was examined from scenes in the South Atlantic anomaly to verify that system noise did not increase there. Calibration pulses during the solar calibrations were used to verify the intergain stability and the detectors (four per band) were checked individually using time delay integration (TDI) data collection sequences during solar calibrations. The island match-up method of Patt, Woodward and Gregg (1997) was used to verify the 1 km navigation accuracy requirement. Ultimately, all acceptance criteria were satisfied within the 90-day period.

One important postlaunch activity is the development of a match-up data set, from which the vicarious calibration is derived using MOBY and coincident satellite $L_W(\lambda)$ data. Match-up data from other sources, such as the AMT Program, are used to validate the operational products. As in situ data are received, the match-up subscenes — 50 scan lines centered on the station location — are extracted from the

Table 1
A summary of the data acceptance criteria for the SeaWiFS instrument before and after launch (non-applicable entries are indicated by N/A)

Item	Prelaunch	Postlaunch
Circular 705 km sun-synchronous noon orbit	N/A	Verified
2 Gbits of GAC and LAC data transmission	Verified	Verified
Real-time LAC with cryptographic information	Verified	Verified
Instantaneous field of view	Verified	N/A
Cross-track scan	Verified	Verified
Sensor tilt fore and aft pointing	Verified	Verified
Dark level measurements	Verified	Verified
Spectral bands	Verified	N/A
Radiometric sensitivity (signal-to-noise ratio)	Verified	Verified
Polarization insensitivity	Verified	N/A
Dynamic range	Verified	N/A
Quantitization	Verified	N/A
Modulation transfer function	Verified	Verified
Individual channel gains	Verified	Verified
Transient response	Verified	Verified
Absolute radiometric accuracy	Verified	N/A
Relative radiometric accuracy	Verified	Verified
System noise measurements	Verified	Verified
Earth location pointing knowledge	Verified	Verified
Radiometric stability and repeatability	Verified	Verified
In-flight calibration data	Verified	Verified

applicable LAC or global area coverage (GAC) image (the former being preferred over the latter). The satellite subscene is linked to the in situ match-up information and archived, so the match-up comparisons can be processed in batch mode with little computational effort whenever processing code or calibration revisions are made.

4. The spacecraft component

The spacecraft component is primarily concerned with the onboard sensor calibration measurements which include solar, lunar, TDI, and intergain calibration observations. Monitoring sensor calibration over periods of a few orbits to several months or years is accomplished using solar calibration for the former and lunar calibration for the latter (Woodward, Barnes, McClain, Esaias, Barnes & Mecherikunnel, 1993; Barnes, Eplee, Patt & McClain, 1999). Solar calibration uses a solar radiation diffuser (Barnes & Eplee, 1996) and an input port located in a fixed position outside of the 117° SeaWiFS Earth-viewing scan interval. The diffuser is covered with an aperture plate with numerous small holes that minimize surface degradation (from contamination or ultraviolet exposure) and adjust the diffuser system output to the required level. To conduct a lunar observation, the entire spacecraft is rotated to allow the sensor to view the nearly full moon once per month, which serves as a very stable, long-term calibration source (Voss, 1994). Internal measurements of interchannel gain and TDI complement these measurements by also providing internal checks on the detectors and instrument electronics.

4.1. Prelaunch spacecraft activities

Calibration and characterization of the SeaWiFS instrument requires: a) prelaunch sensor data, b) results from the instrument certification matrix, c) summaries of the instrument pre-ship review, and d) extensive visitation reports by a Project representative to Raytheon Santa Barbara Research Center (SBRC), the manufacturing site. In addition to the SeaWiFS calibration data provided in Barnes, Barnes, Esaias and McClain (1994a); Barnes, Holmes, Barnes, Esaias, McClain and Svitek (1994b); Barnes, Holmes and Esaias (1995), prelaunch data include measurements of the SeaWiFS diffuser BRDF (Barnes & Eplee, 1996), solar radiance measurements (Biggar, Slater, Thome, Holmes & Barnes, 1993; Biggar, Thome, Slater, Holmes & Barnes, 1995), and comparisons of integrating spheres and transfer radiometers used in the characterization process (Mueller, 1993). The comparison of prelaunch ground-based solar measurements and on-orbit measurements (the transfer to orbit experiment) agree at the ±2% level. Because of the SeaWiFS launch delay, a recalibration was conducted at Orbital Sciences Corporation (OSC) in early 1997 (Johnson, Early, Eplee, Barnes & Caffrey, 1999b) using the GSFC sphere which was recertified by NIST in terms of its original spectral characterization (Early & Johnson, 1996). The SBRC and NIST calibrations agreed to within 5%.

The digital data from the prelaunch calibration and characterization are archived in SeaBASS. The SeaWiFS instrument initially had unacceptable levels of stray light and electronic overshoot which were reduced to acceptable levels by replacing the polarization scrambler, tilting certain focal plane filters, and removing a filter capacitor on each analog-to-digital converter offset network. In addition, the saturation radiance of one detector in each band's 4-detector set was elevated to prevent saturation over bright targets, so a stray light correction algorithm could be implemented (Barnes et al., 1995; Yeh, Darzi & Kumar, 1997). Additional improvements, such as adding a septum to the focal planes and upgrading the primary mirror, were recommended, but not implemented.

Another issue with the instrument, which arose as a result of prelaunch characterization, is the out-of-band response, i.e., the bandpass beyond the 1% transmission values. Various considerations related to the out-of-band response are discussed in Barnes et al., 1994b; 1995; Barnes, Yeh and Eplee, 1996; Barnes, Eplee, Yeh and Esaias, 1997. The problem is the result of an instrument specification that was not strict enough, even though the instrument performance did meet the specification. The effect is most significant in band 8, the primary atmospheric correction band. The operational atmospheric algorithm (Gordon & Wang, 1994a) was modified according to Gordon (1995) to account for the out-of-band response.

4.2. Postlaunch spacecraft activities

Once routine SeaWiFS data collection commenced, daily solar calibrations were taken immediately, and the first lunar calibration followed in November 1997. It was expected that the solar diffuser would degrade and, indeed, over the first 16 months, the 443 nm band showed the greatest decrease (approximately 10%). The solar diffuser has a cover to protect the diffuser from physical damage and contamination (Barnes & Eplee, 1996) during prelaunch and orbit raising activities. Because of the degradation in the diffuser cover, which can only be repositioned once, it will only be removed after degradation has slowed to a negligible rate. The lunar data show no noticeable change in bands 1–6, but indicate significant degradations in the 765 and 865 nm bands over the same period (approximately 2% and 5%, respectively). The changes in the solar calibration data, therefore, is a combination of wavelength-dependent diffuser cover and sensor degradation. While the solar data is not critical for monitoring the long-term stability of the sensor given the lunar measurements, the solar data provide a very smooth time series at a much higher resolution which can provide additional information on high frequency variations in the sensor response.

The lunar calibration data are affected by variations in the lunar phase angle at which the measurements are made and by lunar libration effects which limit the use of the data (Barnes et al., 1999). Of particular interest is the relative calibration between the 765 and 865 nm bands, because their relative calibration is essential for atmospheric correction. Fortunately, these bands appear to have been affected the least by degradation in the diffuser cover. If the time-dependent correction for these two bands, as derived from the coarser resolution lunar measurements, are applied to the solar measurements, the relative change between these two bands is identical, i.e., the diffuser degradation for the two bands is almost the same and can be normalized out. The second reprocessing (August 1998) was executed primarily to correct for degradations in bands 7 and 8. Even though the changes in these bands were small, trends in the derived products were clearly apparent as a result of trends in the atmospheric correction.

5. The atmospheric component

The inversion of radiance to biomass is conceptually straightforward for Case-1 waters where reflectance is determined solely by absorption (Morel & Prieur, 1977), but is more complex for Case-2 waters where reflectance is significantly influenced by scattering and absorption by other constituents. Applications using satellite data are complicated by the fact that the amount of radiance backscattered out of the sea surface is very small compared to the atmospheric contribution; in fact, approximately 90% or more of the signal measured over oceans results from atmospheric radiance (Gordon, 1981). It is crucial, then, to correct the satellite measured radiance for atmospheric effects if quantitatively useful biomass estimates are to be derived. Accurate atmospheric correction requires adjustments for O_3 and O_2 absorption as well as atmospheric pressure variations described in various sensitivity analyses (McClain et al., 1994).

5.1. Prelaunch atmospheric activities

The SeaWiFS atmospheric correction algorithm (Gordon & Wang, 1994a) improves upon the CZCS algorithm (Gordon, Brown & Evans, 1988) which required many assumptions, e.g., $L_W(670) = 0$ and a constant ε (or Ångström exponent) over the entire scene. The SeaWiFS atmospheric correction algorithm is similar to the MODIS oceans atmospheric correction scheme, which was adopted for SeaWiFS under funding to the University of Miami from the CVE. Fraser, Mattoo, Yeh & McClain (1997) verified the Gordon et al. (1988) multiple scattering algorithm using a more complete radiative transfer scheme. Gordon & Wang (1994a) eliminated the use of 670 nm for the correction by using the 765 and 865 nm bands, performed a pixel-by-pixel estimate of ε, and incorporated a Rayleigh-aerosol interaction correction. The University of Miami also addressed the issues of the Earth's curvature on the correction scheme (Ding & Gordon, 1994), O_2 absorption in the 765 nm band (Ding & Gordon, 1995), and surface foam or whitecaps (Gordon & Wang, 1994b). It was also discovered that the plane-parallel assumption induces negligible error for all but the most extreme SeaWiFS scan and solar zenith angle geometries (approximately 65° in the blue part of the spectrum). An O_2 correction of the order of 7% was found to be necessary and has been incorporated into the algorithm. Fraser (1995) found the O_2 absorption to be somewhat higher at about 13%. A wind-speed dependent whitecap correction is also incorporated into the operational processing and has subsequently been reduced by a factor of four.

5.2. Postlaunch atmospheric activities

After launch, data analyses have focused on using the initialization cruise data to verify the atmospheric correction algorithm, at least for marine aerosols. The measurement suite and theoretical rationale are described in Clark, Gordon, Voss, Ge, Broenkow and Trees (1997) and Gordon (1997), respectively. The prelaunch activity did not address three important correction topics: turbid water, sun glint, and absorbing aerosols. Because the atmospheric correction algorithm implements a pixel-by-pixel correction, highly reflective waters with finite L_W values in the near-infrared introduce erroneous estimates of aerosol radiance which can lead to negative L_W values. For coastal areas with limited off-shore expanses of turbid water, ε, values derived from nearby clear water might be used. For large basins where aerosol optical properties can vary, such as the Baltic Sea, this approach would fail. Iterative schemes, such as that developed by Smith and Wilson (1981) for CZCS, are needed. Although the operational algorithm does not explicitly correct for sun glint, most of the glint is removed using a glint mask; much of the remaining glint is removed as part of the aerosol correction, because spectrally it is similar to marine haze. Fraser et al. (1997) showed glint radiance can be estimated using the Cox and Munk (1954) surface slope distribution function and surface wind speeds.

Dust presents a more difficult problem, since its optical properties (e.g., spectral absorption, scattering phase function, etc.) are not well understood. Ishizaka, Fukushima, Kishino, Saino and Takahashi (1992); Fukushima and Toratani (1997) and Fukushima et al. (1998), however, have had some success removing Gobi (yellow) dust effects from CZCS data. Brock and McClain (1992) also showed corrections can be made for Saharan dust if the underlying water is clear, i.e., the $L_{WN}(\lambda)$ values of Gordon and Clark (1981) are assumed. An operational global processing system, however, cannot assume a particular dust model, or that the underlying ocean is clear, and for these reasons it may be some time before a dust correction is possible.

6. The subsurface component

Because of the large atmospheric contribution to the total observed radiances and the great sensitivity of the bio-optical algorithms to the estimated $L_W(\lambda)$ values (Clark, 1981), small errors in the calibration can induce sizable errors in the derived geophysical products, rendering them useless for many applications and, thereby, threaten one of the objectives of the SeaWiFS mission. The subsurface component focuses on $L_W(\lambda)$ measurements, and other related quantities, from ships, moored buoys, and towers to develop a vicarious calibration time series and a geographically diverse set of oceanic and atmospheric observations for product validation.

The diversity of the data sources ensures a combination of space and time series data will be collected. The former are useful for validating the global applicability of the SeaWiFS data, whereas, the latter are useful for calibrating the performance and accuracy of algorithms for interpreting SeaWiFS imagery. The results of both activities are useful for generating new algorithms where deficiencies are detected. The data will be archived (in SeaBASS) and expanded over time from any other expeditions producing data in keeping with the SOOP.

6.1. Prelaunch subsurface activities

The sensor degradation of the CZCS was large (approximately 50% at 443 nm) with significant high frequency variability, which made it clear to the CVE that continuous accurate field observations are essential. A significant source of field data for the Project is derived from its participation in the AMT Program (Aiken & Hooker, 1997). Other sources of data include domestic and international activities:

1. Optical and pigment time series collected from PlyMBODy (Pinkerton & Aiken, 1999) and MOBY (Clark et al., 1997) deployments;
2. Optical and pigment space series collected from deployments of the MOCE Team (Clark et al., 1997);
3. Bimonthly pigment and optical measurements at the AAOT; and
4. Other field expeditions producing data in keeping with JGOFS and SOOP sampling procedures (e.g., the BATS and CalCOFI bio-optical measurement programs).

6.1.1. The AMT program

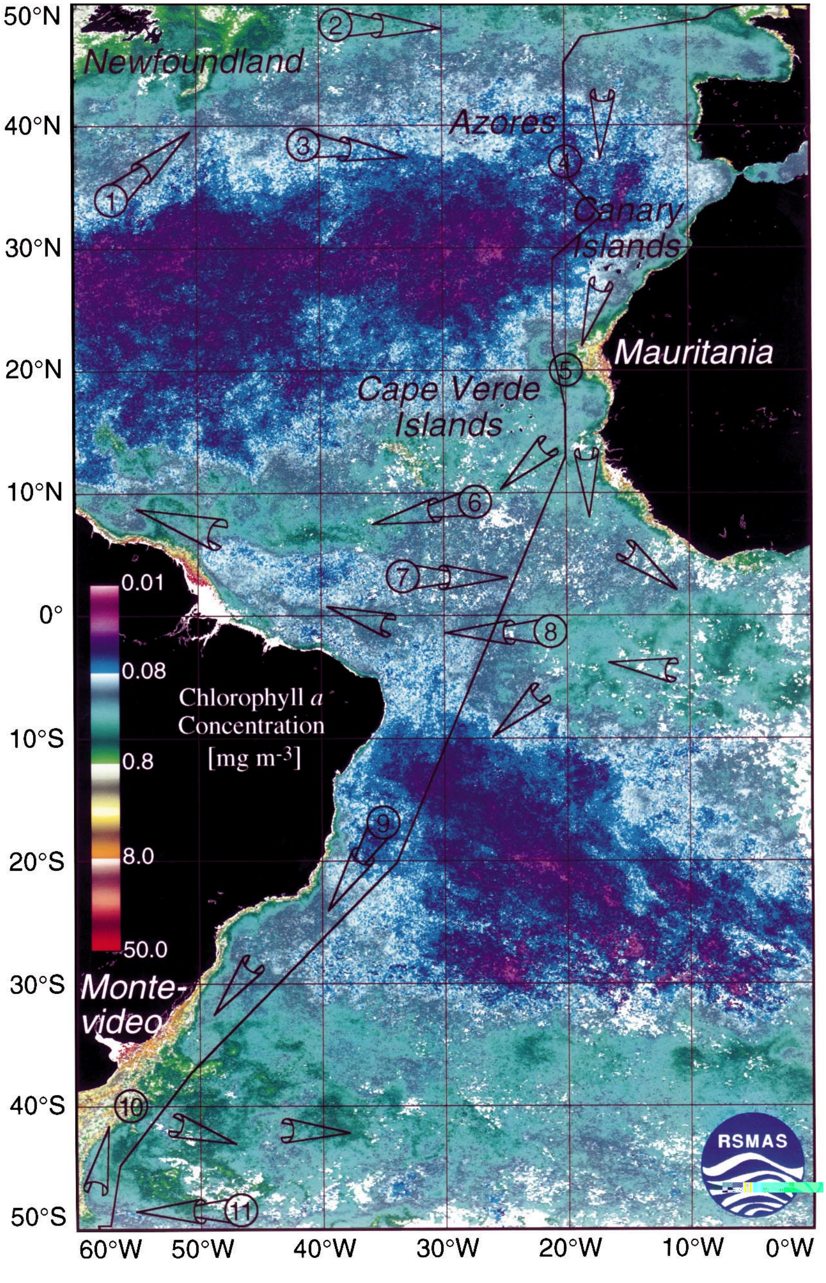
The AMT Program started in September 1995 and at the time of writing there have been eight cruises since then. Fig. 2 depicts the AMT-5 cruise track (which is very similar to all AMT cruise tracks) superimposed on the major current systems of the Atlantic Ocean between 50°N to 50°S, plus a composite SeaWiFS chlorophyll *a* image for the cruise time period. A comparison with Fig. 1 shows how important the AMT transects are for Southern Ocean sampling. To exploit the passage of the JCR, the AMT Program employs three sampling strategies:

1. Continuous, underway, surface layer measurements from pumped seawater of temperature (T) and salinity (S), $p\mathrm{CO}_2$, and nutrients, with discrete measurements (every two hours) of phytoplankton species pigments using the high performance liquid chromatography (HPLC) method;
2. Towed measurements (5–80 m) using the Undulating Oceanographic Recorder (UOR) with sensors for T-S, fluorescence, and transmission (660 nm), plus light measurements at seven SeaWiFS wavelengths; and
3. Daily station measurements, near local solar noon, for hydrographic profiles and water samples to 200m (for pigment concentrations and productivity determinations) plus separate casts for multispectral optical properties with the SeaWiFS Optical Profiling System (SeaOPS), the SeaWiFS Free-falling Advanced Light Level Sensors (SeaFALLS), and the Low-Cost NASA Environmental Sampling System (LoCNESS).

All biogeochemical measurements and all optical measurements adhere to the JGOFS and SOOP sampling procedures. Whenever possible, new instrumentation and novel technologies have been employed to enhance the data acquisition in both quantity and quality; e.g., autonomous $p\mathrm{CO}_2$, the UOR, fast repetition rate fluorometers, SeaFALLS and LoCNESS, as well as the SQM which is used to monitor the stability of the radiometers. All of the radiometers used, including spares, were manufactured by Satlantic, Inc. to ensure redundancy and easy intercalibration. Fig. 3 depicts the primary radiometric instruments used in the AMT Program within the context of the governing calibration and validation equation for SeaWiFS (1). The radiometric activities shown in Fig. 3 were the basis for many of the design elements within the SIMBIOS program.

SeaOPS is composed of two sets of instruments (Robins et al., 1996). The in-water instruments measure $L_u(z,\lambda)$ and $E_d(z,\lambda)$, and are mounted on a T-shaped frame

Fig. 2. The AMT-5 cruise track (which is very similar to all of the AMT cruise tracks except there was no port call in Montevideo) superimposed on a (preliminary) composite SeaWiFS chlorophyll *a* image for the cruise time period plus the major current systems of the Atlantic Ocean between 50°N to 50°S: 1) the Gulf Stream, 2) the North Atlantic Current, 3) the Azores Current, 4) the Azores Front, 5) the Cape Verde Front, 6) the North Equatorial Current, 7) the North Equatorial Counter Current, 8) the South Equatorial Current, 9) the Brazil Current, 10) the Sub-Antarctic Convergence Zone, and 11) the Falkland Current. The white areas in the image are either clouds or no data areas (areas flagged by the processing to prevent spurious results).


50°N
40°N
30°N
20°N
10°N
0°
10°S
20°S
30°S
40°S
50°S
60°W
50°W
40°W
30°W
20°W
10°W
0°W
Newfoundland
Azores
Canary Islands
Mauritania
Cape Verde Islands
Monte-video
0.01
0.08
0.8
8.0
50.0
Chlorophyll *a* Concentration [mg m-3]
1
2
3
4
5
6
7
8
9
10
11
RSMAS

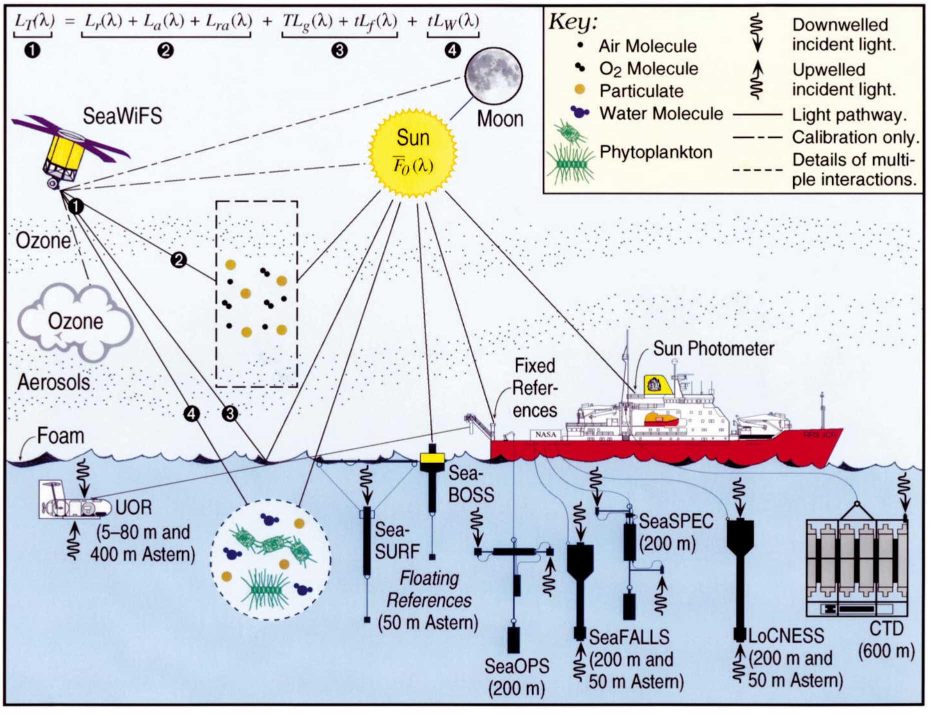


Fig. 3. The primary radiometric instruments used in the AMT Program within the context of the governing calibration and validation equation for SeaWiFS (1). The four numbered bullets refer to the terms identified in (2): 1) total radiance measured at the spacecraft, L_T ; 2) the atmospheric contribution, L_{atm}; 3) the surface (glint and foam) contribution, L_{sfc}; and 4) the subsurface (in situ) contribution, L_{sub}. All of the instruments routinely provide data to the Program except SeaSPEC which is a prototype hyperspectral device that is being refined and evaluated on the AMT cruises. SeaSPEC is manufactured by Analytical Spectral Devices, Inc. (Boulder, Colorado) and has a spectral range of 342–878 nm with a spectral resolution of approximately 0.5 nm. Fiber-optic cables are used to collect light away from the main body of the instrument, and small collector heads are employed to minimize self-shading effects.

which is lowered and raised through the water column by a winch; data are collected during each up and down cast. The above-water component is mounted on a mast and measures the incident solar irradiance above the ocean surface, $E_d(0^+)$. The radiometers have seven channels, which were chosen to correspond with the SeaWiFS instrument wavelengths and bandwidths (Hooker, McClain & Holmes, 1993b), and use a 16-bit analog-to-digital (A/D) converter unit for detecting light over a four-decade range.

SeaFALLS is a rocket-shaped profiler with buoyant fins and a weighted nose that can be deployed quickly by only two people, so the ship can be stopped when light conditions are optimal. The profiler receives its power and sends its data via an umbilical cable while the reference floats away from the ship (Waters, Smith & Lewis, 1990). Once the profiler is approximately 50 m away from the ship (usually astern), it can be dropped to measure $E_d(\lambda)$, $L_u(\lambda)$, fluorescence, plus T-S as it falls freely through the water column.

SeaFALLS is deployed with one or two references which also receive power and send data over a tethered cable: the SeaWiFS Buoyant Optical Surface Sensor (SeaBOSS) measures the incident solar irradiance just above the sea surface, $E_d(0^+,8)$, and can be mounted on a mast or deployed as a drifting buoy, whereas, the SeaWiFS Square Underwater Reference Frame (SeaSURF) measures the incident solar irradiance at a fixed (shallow) depth below the sea surface, $E_d(0^-,\lambda)$, and is floated away from the boat using a buoyant frame. The ability to get the light instruments far away from the ship minimizes any ship-induced disturbances to the in situ light field (Mueller & Austin, 1995). SeaFALLS, SeaSURF, and SeaBOSS are all equipped with 13-channel radiometers (6 channels coincide with the SeaWiFS instrument), which employ 24-bit A/D converters, and are capable of detecting light over a seven-decade range.

The LoCNESS profiler is not a new instrument per se, but instead is built up from the SeaOPS components: the A/D unit and the two light sensors. Once assembled, LoCNESS is a free-falling unit that looks and functions very similar to SeaFALLS, and it is deployed the same way. SeaOPS has two pairs of internal tilt sensors, one pair for when it is oriented horizontally and one pair for when it is oriented vertically. The principle advantage of LoCNESS is its cost and flexibility; it can be assembled from relatively low-cost components (compared to SeaFALLS) and it can be quickly reconfigured, since the radiometers are not integral to the design.

The SQM is an important part of the AMT radiometric measurements. During each of the deployments since its field commissioning, the average stability of the baseline (control) radiometers improved by almost a factor of two for each cruise: 1% for AMT-3, 0.5% for AMT-4, and 0.3% for AMT-5. The improvements were the result of: a) changing the Satlantic radiometers from soft (thermal-evaporative deposition) filters to hard (ion-deposition) filters (a need detected by the SQM), b) increased familiarity with the SQM, and c) continuing improvements to the SQM control equipment and software.

6.1.2. PlyMBODy

Developed at Plymouth Marine Laboratory (PML), PlyMBODy is a moored buoy that carries commercial off-the-shelf (COTS) hydrographic (T-S), fluorescence, and optical sensors which are powered by batteries charged by solar panels (Pinkerton & Aiken, 1999). The analog sensor signals are digitized, compressed, and automatically transmitted back to the laboratory approximately once every two hours over a cellular telephone link. The collection and reporting schedule can be changed anytime to adjust the sampling strategy if required.

PlyMBODy has three 7-channel Satlantic radiometers: two measure L_u (λ) at two different depths, and a third measures $E_d(0^+,\lambda)$. One of the important objectives of the PlyMBODy activity is to demonstrate the capabilities of COTS radiometers for buoy applications—MOBY, in comparison, has hyperspectral one-of-a-kind sensors. Like MOBY, the light sensors are mounted on arms to minimize the self-shading effect of the buoy, and orientation sensors allow the exclusion of data when the optical sensors are behind the buoy or excessively tilted. As with MOBY, mitigation of bio-fouling is accomplished with an aggressive campaign of diver visits to keep the optical windows clean. Coincident casts with an optical profiler are used to monitor data degradation between cleaning sessions and to independently demonstrate the baseline capabilities of the buoy data when the optical surfaces are not contaminated.

6.1.3. The MOCE team and MOBY

The MOCE Team is concerned with the system initialization of the spaceborne scanner, continuing algorithm development, and providing $L_W(\lambda)$ data for sensor calibration verification. All of these functions require in situ radiometric measurements. The MOCE Team will collect data from MOBY and dedicated cruises from diverse areas of the world ocean. For the latter, a full suite of supporting measurements will be made including, but not limited to, particle and pigment analyses, sky radiance, ambient hydrographic and atmospheric fields, and in situ spectrometry (Clark et al., 1997). The CVE invested a substantial amount of its resources into the acceleration of the MOBY development and provided additional funding and manpower support to early MOCE field campaigns. With the combined SeaWiFS and MODIS funding, the MOBY program became operational in July 1997 with three buoy systems supported by a deployment and refurbishment facility established at the University of Hawaii Marine Center in Honolulu.

Verification of a vicarious calibration requires data from a site with minimal variability in optical properties, i.e., open ocean Case-1 water with low pigment concentrations. Also, a large number of in situ and satellite observation pairs are needed to provide statistical confidence in the comparisons, so onboard LAC data collection is routinely scheduled over the field site. For most latitudes, coverage will be every other day, and cloud cover will interfere a significant percentage of the time, so the best approach is a fixed optical mooring (like MOBY) that can be serviced periodically. MOBY provides the capability of collecting data at a higher frequency than the satellite coverage. Additional data will of course be available from ship deployments, but not on a regular basis. MOBY is, therefore, used as the primary data source for vicarious calibration, and shipboard data are used as an independent validation. Choice of the mooring site is a compromise of a number of conflicting requirements — such as, minimizing the possibility of vandalism from boaters while maximizing port access to ensure emergency retrieval. Other considerations include cloud cover conditions, availability of facilities near the harbor for maintenance and staging, and the availability of a suitable vessel for deployment and recovery. At present, the preferred site is off the western coast of the island of Lanai (Hawaii) where the water is optically clear and the atmosphere is predominantly marine haze.

6.1.4. AAOT

The AAOT is located in the northern Adriatic Sea (12.51°E,45.31°N) approximately 15 km east of the city of Venice (Italy). The tower is composed of four levels supported by four pillars sunk into the sea floor. The water depth immediately below the tower is about 17 m, and the height of the upper-most level is 12.7 m above the water. The tower was built in 1975 and is operated by an institute of the Consiglio

Nazionale delle Ricerche (National Research Council) in Venice. During the last two years, monthly visits of approximately 5-days duration have produced an extensive time series of optical, atmospheric, bio-optical, and pigment (HPLC) measurements; the time series is expected to continue for another three years.

The Wire-Stabilized Profiling Environmental Radiometer (WiSPER) system is permanently installed on the AAOT and is operated from the 7 m platform extension on the second level. WiSPER uses a custom-built profiling rig, which was developed with a geometry that ensures all radiometers do not view any part of the mechanical supports. The radiometers are mounted on a 1 m extension boom which puts them approximately 7.5 m from the nearest tower leg. Two taught wires anchored between the tower and the sea bottom prevent movement of the rig out of the vertical plane while it is being winched up and down. The narrow geometry of the rig was designed to provide a minimal optical cross section. Careful attention was paid to the rigidity and stability of the rig, so there is no need for tilt or roll sensors. WiSPER uses the same kind of optical sensors as SeaOPS (and LoCNESS) and all of the instruments have very similar center wavelengths. The processing of the WiSPER data includes the removal of tower shading, bottom reflection, and instrument self-shading effects (Zibordi, Doyle & Hooker, 1999).

6.1.5. Other programs

The philosophy of the SeaWiFS Project is to support field programs whose data can also be applied to other planned missions such as MODIS, and to enhance the development of the bio-optical database with high quality data suitable for satellite calibration and bio-optical algorithm development. In comparison with buoy and tower data, the measurements from ships will be in regions of greater variability, but still primarily in Case-1 waters. Developing algorithms suitable for Case-2 waters is the focus of other groups, as is allocating resources suitable to the task. For example, the Navy working through the Naval Research Laboratory (NRL), National Oceanic and Atmospheric Administration (NOAA), and the Office of Naval Research (ONR) are emphasizing Case-2 water investigations. In addition, at the instruction of NASA Headquarters, relevant MODIS Ocean Team activities were accelerated to meet SeaWiFS objectives and schedules.

During the prelaunch period, the CVE provided support for bio-optical data collection in the Southern California Bight (an augmentation to the CalCOFI program), BATS, and the Gulf of Mexico (an augmentation of the MODIS Oceans Team). Finally, in late 1997, the SIMBIOS Science Working Group field programs began collecting bio-optical data in a variety of locations, all of which are archived in SeaBASS. The algorithm, protocol, and data analysis round-robin activities initiated by the SeaWiFS Project will also be supported by the SIMBIOS program. These joint activities are expedited by the fact that the two organizations are co-located at GSFC.

6.2. Postlaunch subsurface activities

The primary objective of the postlaunch field effort is to maintain the flow of data from the prelaunch activities: the AMT Program, PlyMBODy and MOBY deployments, MOCE cruises, and the AAOT time series, since these receive direct support from the CVE. Within budget limitations, a continuing emphasis is placed on collaborating with other field expeditions producing data in keeping with JGOFS and SOOP sampling protocols. A primary concern is to implement the vicarious calibration procedures to fill in as much of the radiometric and pigment parameter matrix as possible, so the full dynamic range of the algorithms can be validated quickly.

Shortly after launch, the SeaWiFS vicarious calibration was implemented using $L_W(\lambda)$ measurements from MOBY to adjust the calibration to obtain the correct $L_W(\lambda)$ values for coincident match-up data. The vicarious calibration works for bands 1–6, but not for the two near-infrared bands at 765 and 865 nm. The latter are used for estimating aerosol radiance and are assumed to have zero L_W values (Gordon & Wang, 1994a). The prelaunch calibration at 865 nm is assumed, and the calibration at 765 nm is adjusted to yield an ε (765, 865) value typical of marine haze aerosols (1.02–1.06). Based on this approach, a 6% decrease in the prelaunch calibration of the 765 nm band was applied for the first reprocessing (February 1998), but was revised to a 4.4% decrease with the second reprocessing (August 1998) of the SeaWiFS data set (McClain, Cleave, Feldman, Gregg & Hooker, 1998).

The vicarious calibration for the second reprocessing was derived from 53 MOBY match-up data sets collected during the first seven months of operation. In this procedure, the calibration adjustment coefficient for each wavelength is determined by minimizing the mean difference between the satellite $L_W(\lambda)$ values and the measured values. High resolution (1 km) LAC data are used and scan angles are limited to ±45°. The 1 km data collected over the MOBY site are automatically scheduled and stored on board the spacecraft, as is coverage over all validation sites. For the second reprocessing, the adjustment coefficients for bands 1–6 were 1.0137, 1.0003, 0.9698, 0.9904, 1.0003, and 0.9678, respectively.

Global analyses of clear-water pixels (satellite C_a<0.15 mg m^{-3}) from 8-day binned data are used to track trends in the data set. Table 2 summarizes the analysis results for the five 8-day composites spaced evenly throughout the September 1997 to June 1999 time period. The analyses show no discernible trend in any of the average $L_{WN}(\lambda)$ and the corresponding ε (765, 865) values from the clear-water data set. The differences between the MOBY and global SeaWiFS clear-water values result from the fact that most of the SeaWiFS clear-water values are from the central ocean gyres where chlorophyll values are typically lower than at the MOBY site and reflectances are greater. The match-up comparisons show clear trends with a steady decrease in the slope of the linear regression with an increase in wavelength.

Fig. 4 presents a more detailed comparison of the chlorophyll *a* concentrations from the match-up data set. The in situ values were determined using a combination of fluorometric and HPLC methods and the satellite values were calculated from SeaWiFS radiances using the OC2 algorithm. Although the data at low (less than 0.3 mg m^{-3}) and high (greater than 3 mg m^{-3}) concentrations are not usually within the ± 35% limits of the 1:1 line, the majority of the data are (as confirmed by the histogram of the data distribution in the inset panel). The data outside the ±35% limits are usually above the upper limit which suggests the satellite derived chlorophyll *a* values are higher than they should be, although the in situ values could be

Table 2
Summary statistics of the clear-water analysis and the in situ and satellite match-up data. The five SeaWiFS 8-day global level−3 composites averaged 1.29 million low pigment open ocean bins. L_{WN} units are in Wm^{-2} sr^{-1} μm^{-1}. The standard deviation values are computed from the five mean values. MOBY nominal clear-water values are the average of 131 noontime values from different days. The MOBY data were provided by D. Clark and the MOCE team. The match-up analysis shows the slope and intercept for a Type II least squares linear regression along with the number of samples (N) that were considered acceptable for statistical analysis (from a total of 83 possible matchups). The exclusion criteria included the following SeaWiFS masks and flags: land, cloud and ice, sun glint, atmospheric correction failure, high total radiance (values in the high range of the bilinear gain), large solar zenith angle (70°), large spacecraft zenith angle (56°), coccolithophore, negative L_W (bands 1–5), and L_{WN} (555)<0.15 Wm^{-2} sr^{-1} μm^{-1}. A time window of ±4 hours was applied for radiometric and chlorophyll comparisons, and the L_W values were normalized by cos (θ_0), where θ_0 is the solar zenith angle. A minimum of 5 of 9 pixels around a station had to pass all the exclusion criteria, and the ratio of the variance to the mean value had to be less than 0.5

Clear-water analysis			In situ and satellite comparison			
Parameter	Global data	MOBY data	Parameter	Slope	Intercept	N
Chlorophyll *a*	0.088±0.014	N/A	Chlorophyll *a*	0.957	0.016	55
$L_{WN}(412)$	1.93±0.26	1.68±0.17	$L_W(412)$	1.459	−0.037	70
$L_{WN}(443)$	1.73±0.18	1.47±0.13	$L_W(443)$	1.193	0.016	79
$L_{WN}(490)$	1.17±0.07	1.01±0.08	$L_W(490)$	1.002	0.003	81
$L_{WN}(510)$	0.68±0.04	0.60±0.05	$L_W(510)$	0.860	−0.022	78
$L_{WN}(555)$	0.28±0.02	0.26±0.03	$L_W(555)$	0.780	−0.071	81

too low. The in situ data, however, are contributed by a wide diversity of investigators using different analysis laboratories, so it is unlikely they would all be biased on the high side. It is important to note, however, that many of the chlorophyll *a* matchups are extreme values (i.e., their ratios are more than 50% away from the 0.9–1.0 bin interval) and could be considered as outliers. Nonetheless, given the form of the OC2 algorithm in terms of L_W values (O'Reilly et al., 1998), anomalously high satellite chlorophyll *a* values are only possible if the $L_W(490)/L_W(555)$ ratio is too low, i.e., if the $L_W(490)$ values are too small, the $L_W(555)$ values are too large, or both.

Independent verification of the SeaWiFS products (Table 2) is possible using match-up data from a variety of postlaunch deployments. The AMT Program is a primary source of validation data. After screening the data set using a number of QC criteria, only about 2–3% could be used for comparison. A more detailed spectral comparison of satellite and in situ L_W match-up data is presented in Fig. 5. Figure 5a shows the first five SeaWiFS channels in a composite summary. Although the match ups are well distributed with respect to the 1:1 line and the variance in the data is fairly constant over much of the range of radiance levels, biases in the individual channels are discernible, e.g., the 412 nm data are frequently below the 1:1 line indicating that either the corresponding satellite data are underestimated or the in situ data are overestimated. Individual histograms for each channel are shown in

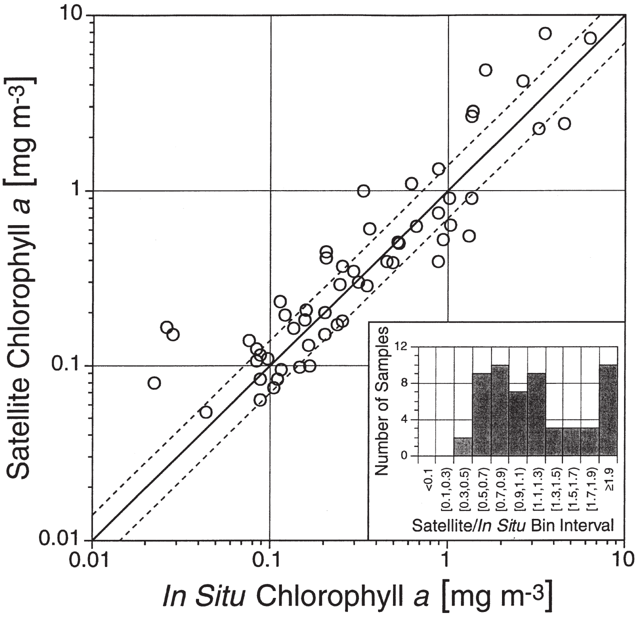


Fig. 4. A comparison of the in situ and satellite chlorophyll *a* concentration values for the match-up data set. The dashed lines delimit the ±35% range of agreement with respect to the 1:1 (solid) line. The inset panel shows a histogram of the data distribution for the ratio between the satellite and in situ values.

Figs. 5b–f. Although all of the channels have peak distributions in the 0.9–1.0 bin interval, there are important asymmetries in several of the histograms.

The 412 nm match-up data (Fig. 5b) are distributed such that more data are below the 1:1 ratio than above, and almost all of the outliers are low (22 of the 23 outliers are low). The 443, 490, and 510 nm data (Figs. 5c–e, respectively) are very nearly equally distributed around the 1:1 ratio (especially the 490 nm data), and they have a smaller number of outliers which are also more equally distributed with respect to the 0.9–1.0 bin interval. The 555 nm data, however, are skewed with more data distributed above the 1:1 ratio than below, including the outliers.

Although it is possible, the bias in the 555 nm match-up data is caused by underestimation in the in situ measurements rather than overestimation in the satellite data, the latter is more likely. The in situ data comes from a wide variety of instruments with differing calibration and usage histories, so it is unlikely they would all measure high. Because the 490 nm data are equally distributed, they cannot explain the apparent bias in higher chlorophyll *a* estimates shown in Fig. 4. The elevated satellite $L_W(555)$ data, however, would result in higher satellite derived chlorophyll *a* values.

Turbid water cases are not included in the analyses, because high reflectance waters are known to introduce an overestimation of aerosol radiance and, subsequently, $L_W(\lambda)$ values. Many Case-1 matchups where chlorophyll concentrations are elevated also result in low L_W retrievals, particularly at 412 and 443 nm. The effect is less pronounced at 490 and 555 nm, and, therefore, has minimal influence on the Case-

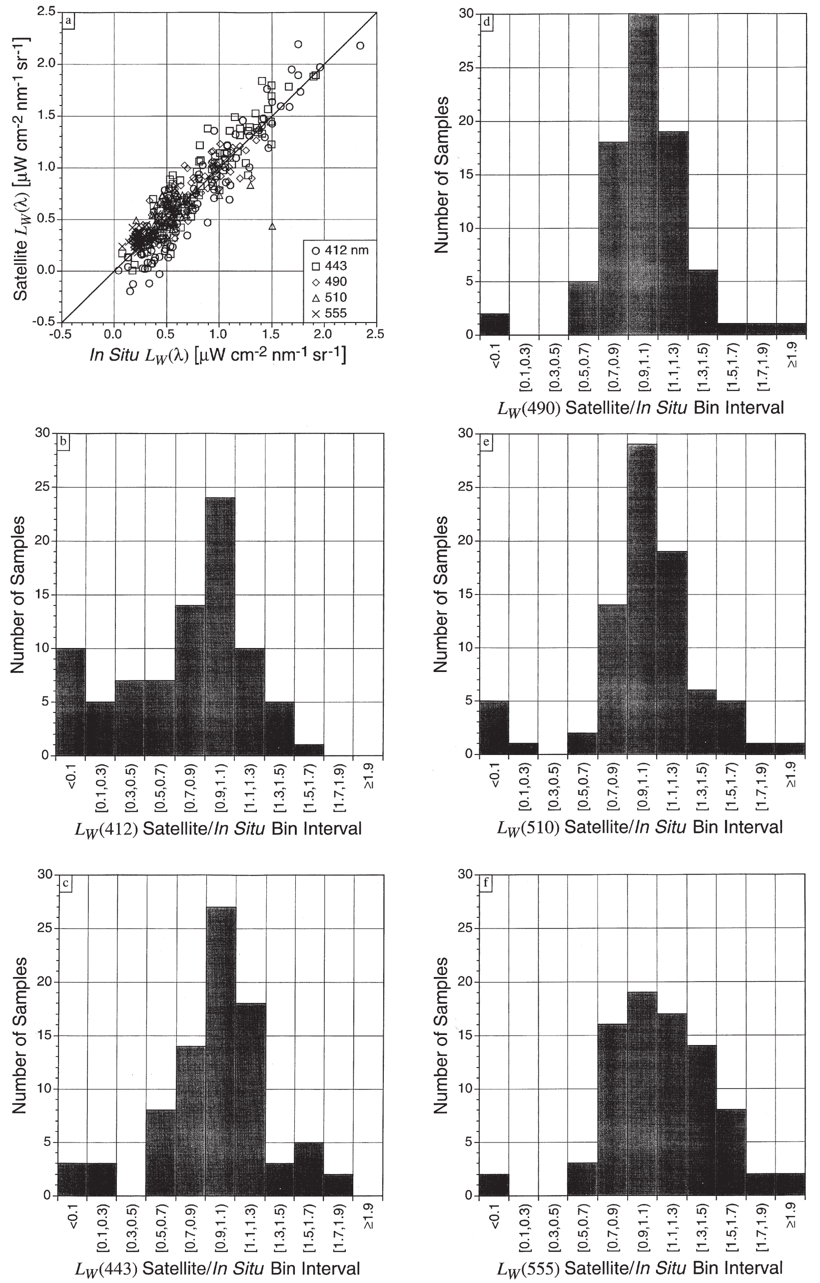


Fig. 5. $L_W(\lambda)$ summaries for the in situ and satellite match-up data set for the first five SeaWiFS channels. A composite summary for all wavelengths is shown in (a) and individual histograms of the satellite to in situ ratio are shown in (b)–-(f). The total number of samples for each wavelength is 83, so 5 samples are approximately 6% of the total.

1 chlorophyll values. In July 1998, the SeaWiFS Project conducted a field campaign at the AAOT to examine this and other related issues and the SeaWiFS Project is pursuing improvements in the atmospheric correction algorithm to account for finite L_W values in the near-infrared, dust detection, residual sun glint outside the glint mask, and overestimation of L_a in clear atmospheric conditions. The low percentage of usable stations during match-up comparisons underscores the difficulty in validating satellite ocean color products, the extreme care that must be taken in collecting the data, and the need for collaboration between ocean color missions to share data and cooperate in the validation process. Nonetheless, the results presented here show that the $L_W(\lambda)$ and C_a retrievals are within the accuracy goals stated above for Case-1 waters. As stated in Section 2, when solutions to the atmospheric correction issues listed above are developed, reprocessing of SeaWiFS data will be executed and the match-up comparisons will be improved.

7. Discussion

Although this presentation is centered on SeaWiFS, the approach is applicable to any ocean color mission. Although all of the activities described should be conducted at some level (depending on available resources), it is recognized that some of the missions scheduled for launch in the next three years do not have comprehensive calibration and validation programs. In those cases, the SIMBIOS program can offer some assistance, since it is modeled after the CVE coupled with the MODIS Ocean Team activities. SIMBIOS will extend the SeaWiFS Project by undertaking the intercomparison of simultaneous satellite ocean color observations in order to intercalibrate and validate data from dissimilar instruments and data collection strategies.

There are limitations to the SeaWiFS Calibration and Validation activity, however, that are largely the result of a limited budget and staff. By itself, the CVE could not implement an in situ sampling program adequate to provide a global bio-optical data set for algorithm development and validation. Augmentations and collaborations with other programs, e.g., MODIS, BATS, AMT, the AAOT, PlyMBODy, and CalCOFI, are essential. Because of the delay in the launch of the SeaWiFS instrument, the Project's budget was well below the prelaunch level which meant that some activities (e.g., the SIRREXs) had to be assumed by the SIMBIOS program, albeit with a more limited scope. Also, the Project could not have independently initiated the development, deployment, and maintenance of a calibration mooring such as MOBY. MOBY has proven to be a reliable source of frequent match-up data and more moorings are needed in areas where algorithm performance, particularly atmospheric algorithms, is in question. Moorings can provide the necessary in situ optical measurements, but not the biological observations. They do require routine maintenance which limit their deployment opportunities. Candidate sites would be off northwest Africa and the northwest Pacific where atmospheric dust can cause problems in deriving valid L_W (λ) values.

Despite limitations, the SeaWiFS CVE has succeeded in many areas while involving the science community in a variety of ways, especially in the areas of algorithm and database development, protocol definition, and calibration round-robins. Each sensor must be calibrated immediately before and after launch — the former requiring laboratory exercises, the latter requiring an initialization campaign in the field — and then each must be vicariously calibrated, i.e., fine tuned, over time with more in situ data to ensure a consistent time series. In comparison to the CZCS mission, the current SeaWiFS approach includes the following unique and noteworthy activities:

1. Implementing a well documented prelaunch sensor calibration and characterization plan including the data analysis products to be produced;
2. Documenting all aspects of the Project in the *SeaWiFS Technical Report Series* (27 of the 43 prelaunch volumes and the current 6 postlaunch volumes are related to CVE activities);
3. Developing and using a fully characterized transfer radiometer (SXR) to ensure intercalibration of the satellite calibration devices;
4. Deployment and regular refurbishment of optical buoys (MOBY and PlyMBODy) and an offshore platform (AAOT) with coincident HPLC pigment and atmospheric sampling for temporally extensive data sets;
5. Spatially extensive field deployments (AMT and MOCE) to collect in situ light and HPLC pigment data;
6. Monitoring the radiometric stability of in situ radiometers at better than the 1% level while they are being used in the field (SQM);
7. Data analysis evaluations for resolving discrepancies in the evaluation data set and selecting operational algorithms (DARR and SeaBAM);
8. Annual meetings of an intercalibration round-robin (SIRREX) team to maintain NIST traceability for key sensors (including the SeaWiFS instrument);
9. Multifaceted on-orbit calibration using solar, lunar, and electronic calibrations;
10. Near-real time QC of all important data streams (satellite imagery, spacecraft engineering, derived products, and ancillary fields);
11. Digital archiving of prelaunch and postlaunch calibration, in situ, and satellite engineering data (SeaBASS);
12. Developing a comprehensive suite of atmospheric correction algorithms which address in detail a variety of topics affecting algorithm performance;
13. Incorporating all level-1, -2, and -3 processing programs into a simplified user-friendly workstation environment (SeaDAS) for distribution to the user community;
14. Continuing participation in the development and deployment of new technologies that increase the likelihood of collecting the highest quality data at the lowest cost (SXR, SQM, and LoCNESS);
15. A comprehensive effort to test, verify, and document all of the operational processing software; and
16. Maintaining a global match-up database for continuous monitoring and episodic vicarious calibration of the satellite products.

Despite its weaknesses, the program has many strengths; most notably, it provides a comprehensive plan for addressing the most important parts of calibrating an ocean color satellite while maintaining a flexible and innovative approach. Provisions have been made to allow the different parts of the calibration and validation process to evolve and for the scientific community to be involved with the data and in formulating many of the strategies used. Indeed, reprocessings of the entire data set were executed 5 and 11 months after routine data collection began. With each reprocessing, substantial improvements in the calibration and derived products were achieved.

The initial validation results are an immediate and quantitative demonstration of the strengths of the SeaWiFS calibration and validation plan:

1. The SeaWiFS instrument has been reasonably stable over the first year of operation with gradual changes in some wavelengths being accurately quantified using solar and lunar calibration data;
2. The vicarious calibration approach using MOBY data and a global match-up database results in consistent global L_W (and chlorophyll *a*) values; and
3. The products meet the accuracy goals over a limited, but diverse, set of open ocean validation sites.

These results also implicitly underscore the benefits derived from the SeaWiFS measurement protocols, the calibration round-robins, the bio-optical algorithm working group, and other prelaunch activities which have made these comparisons feasible so early in the SeaWiFS mission.

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