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An overview of the SeaWiFS project and strategies for producing a climate research quality global ocean bio-optical time series

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Abstract

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project Office was formally initiated at the NASA Goddard Space Flight Center in 1990. Seven years later, the sensor was launched by Orbital Sciences Corporation under a data-buy contract to provide 5 years of science quality data for global ocean biogeochemistry research. To date, the SeaWiFS program has greatly exceeded the mission goals established over a decade ago in terms of data quality, data accessibility and usability, ocean community infrastructure development, cost efficiency, and community service. The SeaWiFS Project Office and its collaborators in the scientific community have made substantial contributions in the areas of satellite calibration, product validation, near-real time data access, field data collection, protocol development, in situ instrumentation technology, operational data system development, and desktop level-0 to level-3 processing software. One important aspect of the SeaWiFS program is the high level of science community cooperation and participation. This article summarizes the key activities and approaches the SeaWiFS Project Office pursued to define, achieve, and maintain the mission objectives. These achievements have enabled the user community to publish a large and growing volume of research such as those contributed to this special volume of Deep-Sea Research. Finally, some examples of major geophysical events (oceanic, atmospheric, and terrestrial) captured by SeaWiFS are presented to demonstrate the versatility of the sensor.
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1. Introduction

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) was the result of a persistent effort by the ocean biogeochemical remote sensing community to have an operational ocean-color satellite following the great success of the experimental Nimbus-7 Coastal Zone Color Scanner (CZCS). Planning activities (Ocean-color Science Working Group, 1982; Joint EOSAT/NASA SeaWiFS Working Group, 1987) paralleled and supported the argument to include global ocean-color observations in the Earth Observing System (EOS; Asrar and Dozier, 1994; King et al., 1999) that ultimately resulted in the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua platforms. The strategy was to have SeaWiFS launch precede the MODIS launch by several years to initiate a global ocean-color time series in support of the Joint Global Ocean

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Flux Study (JGOFS) process studies in the Arabian Sea, equatorial Pacific, and Southern Ocean and to provide ample time to design and validate sensor calibration strategies and algorithms in preparation for the MODIS time series. In addition, SeaWiFS was to be the first in a series of US and international ocean-color missions that would eventually provide a long-term record of ocean biological and optical properties for climate research. In 1990, the NASA Goddard Space Flight Center (GSFC) initiated a competitive ocean-color data-buy procurement and established a SeaWiFS Project Office (SPO).

A data-buy contract with Orbital Sciences Corporation (OSC) was finalized in 1991 with an expected launch in mid-1993. NASA was to have insight, but not oversight, into the spacecraft and sensor design, construction, and testing. Under the contract, OSC was responsible for building, launching, and operating the spacecraft. Originally, the spacecraft was called SeaSTAR, but it was renamed after launch to OrbView-2 when Orbital Imaging Corporation (ORBIMAGE) purchased the spacecraft from OSC. The payment schedule was front-end loaded so that most of the fixed costs were paid at the completion of specific milestones during the prelaunch system development and postlaunch data acceptance phases. After acceptance, fixed monthly payments have been made, subject to penalties if the data quality is less than nominal (to date, no penalties have been applied). NASA's responsibilities included sensor and onboard recorder scheduling (sensor tilting, solar calibrations, lunar calibrations, internal sensor test sequences, and high-resolution data recording), postlaunch sensor calibration, derived product algorithm development, data acquisition [coarse resolution global area coverage (GAC) and fine-resolution local area coverage (LAC)], data processing, research data archival and distribution, and selection of high-resolution picture transmission (HRPT) stations. With these activities in mind, the SPO was organized at GSFC with a project manager, a project scientist, and project element leaders, the elements being Data Capture, Mission Operations (MO), Instrument Science, Calibration, Validation, and Data Processing (DP). Over time, the Instrument Science, Calibration, and Validation elements were merged to form the Calibration and Validation (CV) element.

The prelaunch phase was characterized by an unprecedented level of cooperation between NASA, OSC, and the instrument subcontractor, Hughes Santa Barbara Research Center, given that the contract did not require a high degree of interaction. In fact, GSFC engineering groups made many voluntary contributions towards resolving a number of technical problems with spacecraft components and subsystems, e.g., radiation hardness, power, navigation and attitude control, and telemetry. Throughout the prelaunch phase, OSC demonstrated a firm resolve to achieve success, even at considerable expense to the company. In addition, NASA Headquarters provided steadfast support to the SPO. Despite the best efforts of all parties, the launch schedule slipped 4 years. In August 1997, the prelaunch phase culminated in a flawless Pegasus-XL launch, and SeaWiFS has delivered a continuous stream of GAC and LAC data of unprecedented quality since September 1997.

The original science goals and project objectives, listed in Table 1 (Hooker et al., 1992), were defined to support quantitative research. The initial product suite was very similar to that of the CZCS and included total radiances (level 1 data), normalized water-leaving radiances, chlorophyll-*a*, diffuse attenuation (490 nm), and certain atmospheric correction-related parameters (level-2 products), and binned and standard mapped products at various temporal resolutions (level-3 products), e.g., daily, 8-day, and monthly (Darzi, 1998). The radiometric and chlorophyll-*a* accuracy goals are quite rigorous and have proved challenging to meet. Given the aggressive launch schedule, calibration and validation activities were to be coordinated with those of the MODIS Oceans Team that were already underway. The SPO also sought the science community's involvement in each aspect of the program to capitalize on their expertise, to explore new applications of the data, and to ensure the greatest possible utilization of the data for Earth system science. The SPO benefited greatly from its collaborations with the MODIS Oceans Team, the science community at

Table 1
Original SeaWiFS program goals and project objectives (Hooker et al., 1992)

SeaWiFS program goals	SeaWiFS Project Office objectives
1. To determine the spatial and temporal distributions of phytoplankton blooms, along with the magnitude and variability of primary production by marine phytoplankton on a global scale	1. To serve as the NASA liaison to OSC for the procurement of SeaWiFS data for the oceanographic research community
2. To quantify the ocean's role in the global carbon cycle and other biogeochemical cycles	2. To facilitate the operation and scheduling of the SeaWiFS sensor system
3. To identify and quantify the relationships between ocean physics and large-scale patterns of productivity	3. To develop and validate algorithms for bio-optical properties and atmospheric correction
4. To understand the fate of fluvial nutrients and their possible effects on carbon budgets	4. To characterize and calibrate the SeaWiFS system and to assess on-orbit performance
5. To identify the large-scale distribution and timing of spring blooms in the global oceans	5. To achieve radiometric accuracy to within 5% absolute and 1% relative, water-leaving radiance to within 5% absolute, and chlorophyll-*a* concentration to within 35% over the range of 0.05–50.0 $mg\,m^{-3}$
6. To acquire global data on marine optical properties, along with a better understanding of the processes associated with mixing along the edge of eddies and boundary currents	6. To collect, archive, and process recorded data, as well as global maps of bio-optical properties and chlorophyll-*a* concentration for the research community
7. To advance the scientific applications of ocean-color data and the technical capabilities required for data processing, management, and analysis in preparation for future missions.	7. To provide quality assurance monitoring of, and coordinate collection of, direct broadcast data by NASA's selected LAC receiving stations
	8. To support the SeaWiFS Science Working Group (SWG).

large, and the Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) program (Fargion and McClain, 2002; McClain et al., 2002) which provided processing algorithms, in situ data sets, and much guidance.

The purpose of this paper is to review the original science goals and project objectives, outline the approaches pursued to achieve them, and assess (as quantitatively as possible) the overall level of success in attaining them. During the 12-year history of the SPO, a number of innovative approaches have been developed in addressing certain problems, e.g., the lunar time-dependent calibration correction. In some cases, the SPO has needed to adjust its approach when initial strategies proved ineffective or to take advantage of new technology, e.g., the evolution of the data system design. In the end, it is hoped that the SeaWiFS program can be used as a model for future missions and that the infrastructure the SPO helped establish can be continued and expanded in anticipation of future missions such as the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP).

2. Project philosophy, functions, and approaches

Because SeaWiFS was a data-buy rather than a standard NASA mission, the SPO was established in the Earth Science Directorate (Code 900) at GSFC with almost all elements of the SPO being co-located and lead by ocean scientists. By having scientists with vested interests in the data as element leaders, a commitment to data quality and data access, and a focus on research and development in every aspect of the mission was ensured. While the SPO managers and element leaders have been civil servants, the majority (roughly 80–90% in the postlaunch phase) of the SPO personnel have been on-site contractors provided under support services contracts defined, competed, and negotiated by the SPO management. This helped ensure that the SPO received the best support possible. Nonetheless, training was necessary, as the majority of the contract staff were from other science disciplines. For instance, the CV element conducted a comprehensive literature review to familiarize the staff with all aspects of ocean-color satellite calibration and algorithm development, as well as the community with whom they would be working.

The SPO has been committed to a number of specific objectives (listed below) related to, but not explicitly identified in, the overall SeaWiFS program objectives outlined in Table 1. Many aspects of the SeaWiFS program were a result of the lessons learned from the proof-of-concept CZCS program and include the following.

1. A comprehensive calibration and validation program spanning the entire mission. For the CZCS, the postlaunch calibration and validation program was supported for only the first year and, therefore, did not include time series observations to track sensor performance. In addition, the field program for algorithm development was limited mainly to areas near North America.
2. Rapid user access to data products. CZCS data did not become generally available until the global reprocessing was completed (Feldman et al., 1989), several years after data collection ended.
3. Availability to the user community of a low cost data processing capability. The Nimbus Project did not provide data processing tools, not even to the Nimbus Experiment Team (NET). As a result, individual groups independently developed their own software such as SEAPAK (McClain et al., 1991a, b, 1992a) and the University of Miami DSP software.
4. The ability to reprocess the entire data set on a routine basis. The CZCS reprocessing required the entire data set be staged on optical media from over 30,000 9-track tapes. This process alone took over a year to complete. The vicarious calibration of the entire data set required processing the data many times to get consistent results (Evans and Gordon, 1994) and took a similar amount of time. The final processing and quality control took at least another year. Recently, the CZCS data was reprocessed (at reduced resolution) by Gregg et al. (2002) to be consistent with the third SeaWiFS reprocessing in 2000.
5. The processing system must be tightly coupled to the science. None of the NET members were located at GSFC where the processing was being conducted. NET meetings (Acker, 1994) provided opportunities to review results and advise the Nimbus Project, but these meetings were relatively infrequent.

While none of the SPO staff were members of the NET, many had worked extensively with the CZCS data and some had worked closely with the NET in the postlaunch period. Thus, there was an understanding of what needed to be done differently in an operational setting as opposed to a proof-of-concept scenario. Specifically, particular attention was paid to the following strategies.

1. *Direct community involvement in, and awareness of, all SPO activities*. This has been accomplished through open project reviews, workshops, calibration and data analysis round robins, periodic project status reports broadcast to the community (especially important in the prelaunch phase), annual science team meetings, professional conference presentations, and support of a SeaWiFS booth at major US conferences. The SPO has relied on the community to provide the atmospheric correction and bio-optical algorithms and most of the in situ data (atmospheric and bio-optical) for algorithm development and post-launch product validation. To finalize the chlorophyll-*a* algorithm before launch, a special workshop involving in situ bio-optical data processing and real time algorithm comparisons was conducted at the University of California/Santa Barbara ([91]O'Reilly et al., 1998). During each of the four reprocessings, the SPO actively sought the community's input by hosting workshops and posting descriptions and analyses of proposed processing modifications on SPO Web sites.
2. *Rapid turnaround and easy access to data products*. The goal was to process the data on a same-day basis with release to the science community at the earliest possible time allowed under the data-buy contract. One approach

was to design the data formats to be self-describing with the relevant ancillary and calibration data files cross-referenced and automatically distributed with the associated image data file. Data selection was simplified with on-line image browsing.

3. *Focus on a few key geophysical products*. The number of archive products was kept to a fairly small number of key geophysical parameters with one product per parameter. Also, a single set of data quality masks and flags was used. The product suite was revisited at each reprocessing to remove products of little interest (e.g., CZCS pigment) and add others (e.g., photosynthetically available radiation, PAR) based on community input.
4. *Affordable user-friendly end-to-end processing tools for the most common computer systems used by the science community*. This was considered essential if the data were to be fully exploited and resulted in the SeaWiFS Data Analysis System (SeaDAS). SeaDAS was primarily supported under separate funding from the NASA ocean biogeochemistry program, but has required additional SPO involvement and financial support (hardware, system administration, and SeaWiFS software technical support).
5. *Science quality data by the end of the 90-day data acceptance period with occasional reprocessings*. The CV element implemented a comprehensive set of test and evaluation criteria and analysis software prior to launch. During the postlaunch data-acceptance period, all criteria were quantitatively evaluated, and the first reprocessing was initiated immediately afterwards. Three subsequent reprocessings incorporated calibration and algorithm updates to further improve the data quality.
6. *Full documentation and disclosure of SPO supported activities, operational algorithms, sensor characteristics, etc*. The SPO has supported a full-time technical editor since early in the program and has published nearly 70 technical reports, plus numerous conference and journal papers. These documents have been distributed at the time of publication to a subscriber list of nearly 500 individuals.
7. *A rigorous scrutiny of all aspects of ocean-color remote sensing technology, measurement science, and algorithm development with an emphasis on innovation and improving the science community's technical infrastructure and ability to support ocean-color satellite missions*. This has been accomplished primarily through activities such as the calibration and data analysis round robins, measurement protocol development, in situ instrument technology development, and the SeaWiFS Bio-optical Archive and Storage System (SeaBASS). Also, while the project's CV staff needed to be familiar with all processing algorithms and knowledgeable of the related scientific literature, algorithm development was left to the science community, so the SPO would be impartial in its independent implementation and evaluation of algorithms. One exception is the lunar calibration algorithm used to track the sensor's stability, which was developed by SPO staff. This methodology continues to be refined and, with recent US Geological Survey high-resolution reflectance models of the lunar surface, may provide absolute calibrations of the sensor.
8. *SPO flexibility, evolution, and accountability in its approach to scientific and operational development activities*. Each SPO element manager was given complete control on defining the technical approach. As a result, all elements adopted a strategy of continual evolution in the technologies and approaches to be pursued. For instance, the data processing element has annually expanded and replaced systems to continually upgrade with new technology. In fact, the original SPO-wide computing design was three Unix servers connected to X-terminals. Over time, the X-terminals were replaced by Unix workstations, which have recently been replaced by PC Linux systems. To ensure communication between elements and with management, especially in the prelaunch phase, the SPO conducted periodic open reviews (roughly every 6 months) of each SPO element with members of the staff giving

overviews of the components they were responsible for developing.

9. *Community support and user services*. The SPO saw the community as a vested partner and recognized that overall success would be largely determined by the community's attitude towards the SPO. With the element leads being active scientists, they understood the community's needs. Examples of support services include SeaDAS, near-real-time image support, and the pre- and postlaunch SeaWiFS Technical Report Series (STRS).
10. *Fiscal accountability and openness*. The budget guidelines for the SPO and each SPO element were established when the SPO was organized and approved by NASA Headquarters. The allocations for the SPO elements have not changed since then, although some elements have merged over time. Each element manager was given complete control over the budget for that element, which gave the element manager the ability to adjust his budget priorities over time, e.g., manpower, hardware, university grants, international agreements, and contracts. The SPO has always been committed to operating within budget and not requesting additional overguide funding. Because of the launch delay, however, a one-time request for overguide funding was made and approved in order to have flat funding during the operational phase.
11. *New products and applications beyond ocean biogeochemistry*. The SPO has striven to promote the usefulness of SeaWiFS data by exploring new ocean, terrestrial, and atmospheric products, many of which are possible because the sensor does not saturate, even over bright land and clouds. After the third reprocessing in 2000, the SPO began routine production of a number of "evaluation" products, e.g., PAR and color dissolved organic matter (CDOM), for the community to consider as potential archive products. The evaluation products were derived using algorithms provided by the community. The SPO has worked with researchers in the atmospheric and terrestrial science communities to provide products such as aerosol optical thickness (AOT) and the normalized difference vegetation index (NDVI). Subsets over the MODIS land validation sites for the entire mission are available via the SeaWiFS Web site. Examples of such interdisciplinary use of the data are Behrenfeld et al. (2001), Wang et al. (2000), and Chou et al. (2002).
12. *Tightly coupled and highly interactive SPO elements*. It was recognized that all elements were interdependent and required a high degree of communication and mutual understanding. For example, near-real time quality control procedures by the CV element were embedded in the data processing sequence and affected the processing system design and throughput. *Mission requirements.* The SeaWiFS program goals and project objectives (Table 1) were considered to be requirements or criteria for mission success.
13. *SPO focus on mission deliverables*. The staff has always focused on improving services to the community, the accuracy of the data products, and outreach. The SPO has purposely avoided committing project resources to investigations of ocean or Earth science, although staff occasionally assist groups in getting access to data products for specific studies.

The following sections outline the activities and accomplishments of the SPO organizational elements. One of the important aspects of the SPO is that all elements are co-located allowing continual communication between the groups and the sharing of resources (personnel and equipment). Co-location also helps the SPO to be very efficient in terms of decision making and oversight of SPO activities. The order of the sections reflect the data flow, i.e. mission operations, data capture, calibration and validation, data processing, and data archival and distribution. Fig. 1 provides a graphical description of the data handling process.

2.1. *Mission operations and data capture*

The goal of the MO element of the SPO was to maximize the collection of scientifically useful data from the SeaWiFS instrument through a close working collaboration with the engineers and

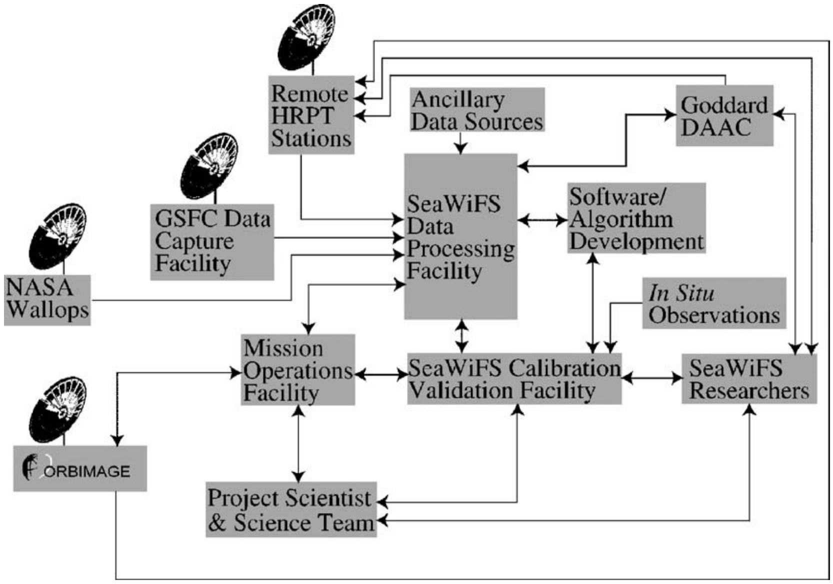


Fig. 1. SeaWiFS data flow from satellite to data user.

mission planners at ORBIMAGE, the other elements of the SPO, and the global ocean-color community. While ORBIMAGE is responsible for the actual operations of the OrbView-2 spacecraft and SeaWiFS instrument, NASA has the responsibility for (a) SeaWiFS instrument command scheduling and onboard recorder management; (b) navigation, including position determination, attitude determination and geolocation (Patt and Gregg, 1994; Patt et al., 1997; Patt, 2002); and (c) routine spacecraft and instrument health and safety monitoring. A representative daily SeaWiFS data collection schedule is presented in Fig. 2.

To accomplish the data acquisition tasks indicated in Fig. 2, NASA is responsible for providing ORBIMAGE with the specific scheduling requirements each week for data collection by the SeaWiFS instrument including defining the operating parameters (gain, tilt, start/stop times, targets), calibration activities (solar, lunar, time-delay integration) and coordinating the downlink schedules with the primary S-band downlink site at NASA Wallops Flight Facility (WFF). ORBIMAGE integrates NASA's scheduling requirements into their routine spacecraft operations schedules that are then provided back to the Mission Operations group for final verification before uplink to the spacecraft by ORBIMAGE. Special requirements—such as spacecraft emergencies, downlink scheduling conflicts at WFF and requests for high data rate acquisition of telemetry information to help resolve potential spacecraft anomalies—are handled on a case-by-case basis. Extensive prelaunch end-to-end system tests, and regular postlaunch communications with ORBIMAGE, including joint annual reviews, have resulted in a smooth, efficient, and mutually beneficial collaboration.

Over the 5 1/2 years of operation, there have been approximately 20 unscheduled safe-haven events due to onboard system anomalies that have resulted in some loss of science data. During these events, the SeaWiFS instrument is stowed, and the majority of the OrbView-2 systems are put into a 'protective' posture waiting for a signal from ground controllers to resume routine operations after whatever event that triggered the safe-haven is identified, analyzed, and the corrective actions needed for full recovery are executed. The majority of these events have been associated with single-event upsets in one of the spacecraft electronic subsystems, and most of these events have been

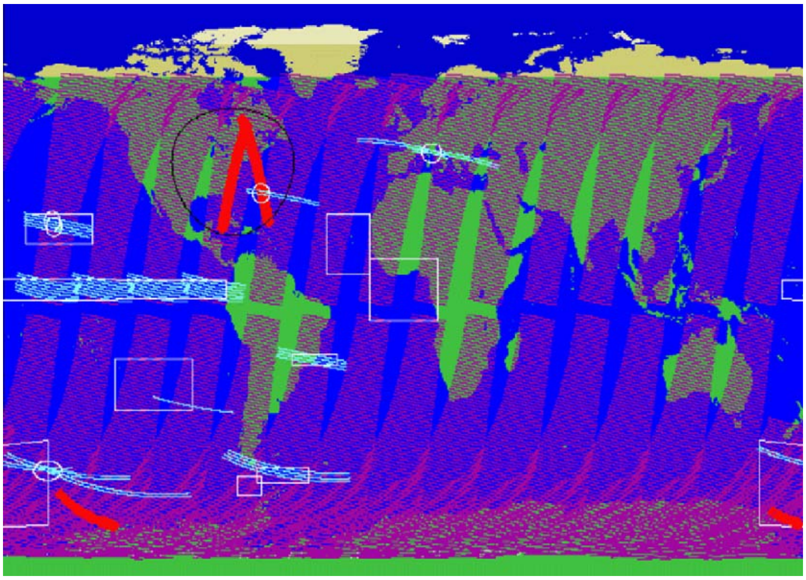


Fig. 2. SeaWiFS data acquisition on 1 January 2002. Illustrated are the standard 14 orbits of GAC data collected each day (purple shading), the specific high-resolution LAC targets (blue shading with wider swaths), daily time-delay integration and solar calibration data (short LAC swaths at high southern latitudes colored red) and the two S-band downlink opportunities (red) over the US east coast. The GAC data collection is truncated at scan angles of $\pm 45^{\circ}$. The limited onboard LAC coverage ($\sim$10 min per day) is scheduled in advance to cover in-water calibration targets (white elipses or circles), ships of opportunity collecting validation data, the solar calibration data, and regions of either specific scientific interest (white boxes; lowest priority).

shown to occur while the spacecraft is flying through the South Atlantic Anomaly, an area east of Argentina where solar particle fluxes are elevated. As knowledge of these events developed, and as confidence in the recovery procedures was improved, the duration between the onset of safe-haven events and full recovery has greatly decreased such that most events are recovered within 12 h. In addition to these unplanned events, the spacecraft has been intentionally placed into a protected, safe-haven posture during the peak activity periods of the past four Leonid meteor showers as a precautionary measure. In spite of these unplanned interruptions to normal operations, however, more than 98.5% of the potentially available data has been successfully acquired and processed.

The MO element works with ORBIMAGE in tracking the health of the spacecraft and the SeaWiFS sensor. Each conduct their own evaluations. The MO element carries out regular analyses of the spacecraft and instrument telemetry with each downlink and posts this information on the Web. Daily and long-term plots of the behavior of the major onboard subsystems including battery performance, horizon sensor parameters (phase and chord), telescope motor temperature and current, sun-sensor telemetry trends, and momentum wheel performance are tracked and permit continual assessment of the health and safety of the spacecraft and instrument. These analyses are also crucial in maintaining functionality and improving the performance of the spacecraft over time. Many of the prelaunch concerns about the longevity of a number of the spacecraft systems were completely resolved through these analyses. Plans for an extended mission beyond the original 5 years have used the long-term trend analyses to assess the potential viability of the spacecraft and instrument. Presently, there is no indication of any significant degradation in the spacecraft subsystems.

To meet the mission geolocation accuracy goal (less than one pixel), members of the SPO developed an intimate working knowledge of the spacecraft design and operation, especially the attitude control system (ACS). OrbView-2 has a relatively simple ACS that consists of redundant sets of sun and horizon sensors that are used to determine the pitch, roll, and yaw of the spacecraft. More sophisticated satellites have star trackers and gyroscopes. The ACS sensors provide input that is used to control the momentum wheels and torque rods (coils that work off the Earth's magnetic field) that adjust the spacecraft attitude to maintain the sensor at a nadir orientation. Maintaining the ACS in an optimal configuration includes periodic adjustments of some sensor parameters and fine tuning of sensor alignments. Bilanow and Patt (2004) provide a summary of some of the major SPO contributions to the spacecraft ACS support.

In addition, an automated technique of island target matching was developed (Patt et al., 1997) and the results are continually updated and posted on the Mission Operations Web site with the resulting improvements to the navigation software incorporated into the operational and SeaDAS navigation procedures as appropriate. Over the life of the mission, an average of approximately 50 island targets per GAC swath have been acquired and analyzed. For the 1.1 km HRPT data that the SPO routinely receives, an average of more than 100 targets per scene are matched, yielding an average error of 1.03 km, meeting the mission's geolocation requirement.

The SeaWiFS instrument has a nominal resolution of 1.1 km at nadir, but because of limitations in onboard storage and telemetry technology in the early 1990s, it was not considered cost effective to store and downlink the global 1-km data set. Consequently, the full-resolution data are subsampled by every fourth pixel and every fourth line, and this global data set is stored onboard with limited amount of high-resolution data. Twice per day, at approximately local noon and midnight, the spacecraft downlinks the recorded data as it passes over WFF. To minimize single-point failures that would result in an irrecoverable loss of science data, the SPO installed its own dual S and L-band receiving station at GSFC prior to launch. This fully automated receiving station serves as the primary L-band receiving station for the US East Coast and as the S-band backup for the primary station at WFF. For a number of reasons, including conflicts at WFF caused by Space Shuttle operations and antenna-related issues, the station at GSFC frequently serves as the primary data telemetry site and has not missed a single downlink.

In addition to the two NASA stations, the SPO collaborates with a network of approximately 124 L-band receiving stations around the world that are affiliated with universities, research organizations, and other space agencies to collect the LAC data that are broadcast as the spacecraft passes over the stations several times per day. The vast majority of these ground stations are independent and are not supported with NASA funds. The SPO provides the coordination between the ground stations and ORBIMAGE for real-time decryption of the data in support of research activities or demonstration projects and through NASA-provided software. This software is distributed to the ground stations, and facilitates the collection, processing, archive and distribution of data collected by these stations. Under terms of the data-buy contract, NASA is authorized to collect and decrypt SeaWiFS data in near-real time from any 12 of its authorized receiving stations (in addition to the station at GSFC) at any given time, while the remaining stations are allowed to collect SeaWiFS data, but must wait at least 14 days before ORBIMAGE provides them with the appropriate decryption keys, which allows them to process the data. At present, there are four stations covering the continental US that have been granted permanent real-time licenses, an equal number of international stations have long-term floating licenses, and four short-term floating licenses are available at 2-week intervals to support specific near-shore research activities not covered by the existing near-real-time stations or for ship-based receiving stations. The success of this activity is quite remarkable and has far exceeded the initial SPO goal of coordinating a network of 12 receiving stations as outlined in the contract. To date, the SPO has received approximately 128,000 HRPT files from 88 receiving stations. Like the GAC and onboard LAC data, these are quality controlled and transferred to the GSFC Distributed Active Archive Center (DAAC) for distribution.

2.2. Calibration and validation program

As outlined earlier, the scientific applications of satellite ocean-color data require an extremely high radiometric accuracy of both the sensor calibration and the derived water-leaving radiances. Because of these stringent accuracy requirements, a comprehensive calibration, validation, and quality control program was conceived (McClain et al., 1992b, 1996) for the SeaWiFS, which would continue throughout the mission. The program included sensor calibration and characterization (pre- and postlaunch), bio-optical algorithm development, atmospheric correction algorithm development, postlaunch near-real-time quality control, and a field measurement program that included support for moored buoys (e.g., the Marine Optical Buoy, MOBY), oceanographic research cruises (e.g., the California Cooperative Fisheries Institute, CalCOFI surveys), and time series stations (e.g., the Bermuda Atlantic Time-series Station, BATS). The SeaWiFS CV element had a budget profile that peaked at around $ 2 million per year early in the program in anticipation of a 1993 launch and declined by 1997 to a steady level of about half of the peak year funding. The rationale was to take advantage of the MODIS Ocean Team activities, which were also in the early phases of development, and accelerate some of their activities, e.g., the atmospheric correction algorithm, with additional funding to meet the earlier SeaWiFS launch schedule. Fortuitously, as the SeaWiFS calibration and validation budget began to ramp downwards, the SIMBIOS program was initiated in 1996 as a result of dropping the EOS Color mission, a second data-buy to follow SeaWiFS, from the EOS program. SIMBIOS included a number of data collection investigations by a separate science team and the SIMBIOS Project Office, which provided a much more diverse global bio-optical and atmospheric data set than would otherwise been available (McClain and Fargion, 1999; Fargion and McClain, 2002). The amount of data provided was greatly increased by the SIMBIOS Project's support of bio-optical and sun photometer instrument pools and its augmentation of the Aerosol Robotic Network (AERONET; Holben et al., 1998) with 12 coastal and island sites.

A critical step in achieving the necessary radiance accuracies is to have a well-characterized satellite instrument. During the prelaunch phase, considerable attention was focused on the calibration and characterization of the SeaWiFS instrument (Barnes et al., 1994a, b; Johnson et al., 1999a). After launch, a broad-based field program is required for on-orbit calibration and product validation. These activities during the CZCS era relied exclusively on a small number of ship and aircraft campaigns, which proved to be inadequate to sufficiently quantify the degradation in the CZCS instrument (Evans and Gordon, 1994). It was also recognized that the sensor characterization and field data sets must be internally consistent, readily available, and well organized in order to expedite algorithm development and postlaunch validation. This led to the SeaWiFS Intercalibration Round-Robin Experiments (SIRREX), the bio-optical measurement protocols, and the development of SeaBASS (Hooker et al, 1994; Werdell and Bailey, 2002), which was subsequently expanded to include atmospheric validation data under SIMBIOS support (Fargion et al., 2001). In the postlaunch phase, the calibration round robins, bio-optical protocol development, and SeaBASS have been largely supported by the SIMBIOS program.

While the SPO purposely avoided algorithm development, it did take the lead in organizing and orchestrating a community-wide algorithm development and evaluation through a series of prelaunch workshops such as the SeaWiFS Bio-optical Algorithm Mini-workshop (SeaBAM; O'Reilly et al., 1998). Summaries of each workshop were published in the index volumes of the prelaunch STRS. Once the SIMBIOS program started, the annual SIMBIOS science team meetings provided a forum for such discussions and the need for the SPO to host workshops was superceded, except in special occasions, e.g., reprocessing workshops. With each reprocessing, both the

SPO and members of the user community have suggested processing modifications, which have been openly discussed and evaluated with the community at large. For instance, the chlorophyll-*a* algorithm was replaced with the third reprocessing (O'Reilly et al., 2000).

One of the MODIS ocean team activities that was accelerated for the original SeaWiFS launch schedule was the development of the MOBY (Clark et al., 1997). MOBY was to be the primary vicarious calibration site for the MODIS and SeaWiFS missions and was initiated under the MODIS program. The SPO provided substantial support for MOBY development prior to launch through a contract with Moss Landing Marine Laboratory. Continuous MOBY deployments and data collection began in July 1997, just before the launch of SeaWiFS. Since then, financial support from the SPO has been for MOBY maintenance ship time, albeit at a much reduced level than during the MOBY development phase. MOBY has provided a continuous time series of high quality water-leaving radiances since the summer of 1997. The strategies for using MOBY have differed somewhat between the MODIS and SeaWiFS. SeaWiFS is able to view the moon monthly at the same phase angle, so lunar data are used to characterize the time trends in the sensor responsivity (Barnes et al., 1999, 2001) and MOBY data are used to adjust the prelaunch gains (Eplee et al., 2001). MODIS is a more complex system and the lunar measurements and solar diffuser measurements analyzed by the MODIS characterization and support team (MCST) are not at the precision required for ocean-color applications, so MOBY data are used by the MODIS Oceans Team to fine tune the time-dependent calibration gains provided by the MCST.

By the third SeaWiFS reprocessing in 2000 (McClain et al., 2000a, b), the strategy for calibrating SeaWiFS on-orbit and for validating products was fairly mature and incorporated a variety of elements shown in Fig. 3. The strategy included rigorous evaluations of sensor performance characteristics and calibration prior to launch, comparisons of the pre- and post-launch

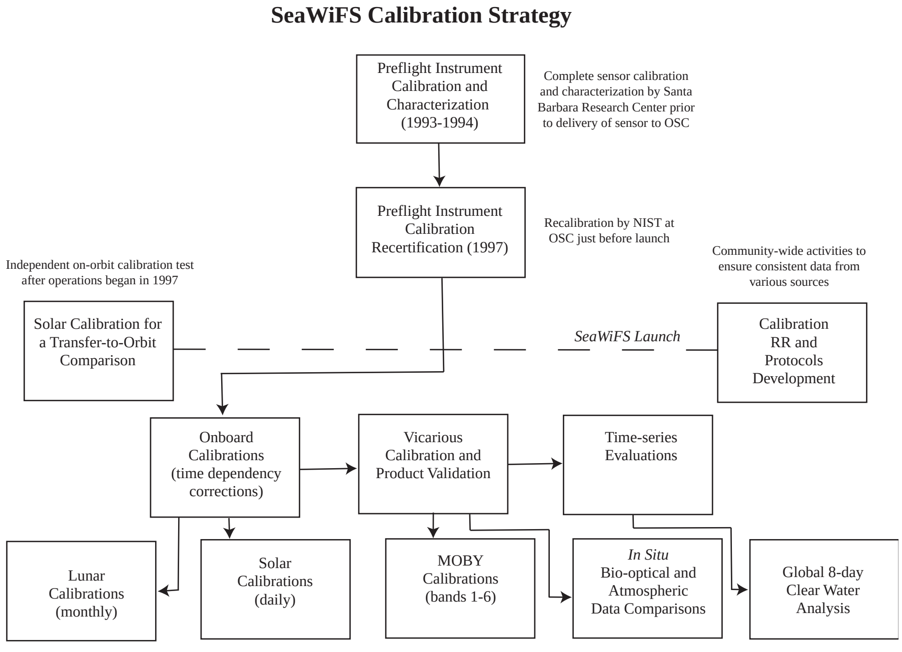


Fig. 3. SeaWiFS calibration and validation scheme showing pre- and postlaunch activities and analyses.

sensor calibrations (the so-called "transfer-to-orbit" experiment), lunar and solar analyses of on-orbit sensor degradation, the MOBY-based vicarious calibration adjustments to the prelaunch laboratory calibration gain factors, time-series analyses of global normalized water-leaving radiances (L_{WN}), atmospheric correction epsilon values, and chlorophyll as additional sensor stability indicators, and match-up analysis of satellite-derived versus in situ measured values (bio-optical and atmospheric) for product validation. The approach and results of the CV element have been well documented in the STRS, conference papers, and journal articles as a result of the SPO's emphasis on information sharing, community infrastructure development, and accountability. All these documents have been disseminated to a SPO distribution list of approximately 500 individuals, universities, and libraries and are available upon request from the SPO. Summaries of results have been published (McClain et al., 1998, 2000a, b; Hooker and McClain, 2000; Barnes et al., 2001, Eplee et al., 2001) and will be updated as new results become available, e.g., the evaluations of the fourth global reprocessing of the entire SeaWiFS data set.

The original SPO strategy was to rely solely on field bio-optical measurements for algorithm development and validation collected by the community, and funding was provided to augment CalCOFI, BATS, and other data collection programs. Indeed, the outside research community has provided over 50,000 biological stations and over 5000 discrete sun photometer observations (plus 94 field campaigns of shadow-band radiometer data) to SeaBASS. It eventually became apparent, however, that a number of in situ instrument design, calibration metrology, measurement protocol, and data processing issues and uncertainties could not be addressed by simply augmenting ongoing field programs. Examples include measurements in turbid water and protocols for above-water measurements of water-leaving radiance. As a result, a separate SPO capability focused on understanding and reducing the uncertainties was instituted. The next three sections—SeaWiFS sea truth data accuracy considerations and advancements; Field instrument development and evaluation; and the SeaWiFS Project field program—summarize a number of the subsequent activities and achievements of the SPO's field measurement program. These activities are interdependent and were conducted in parallel, but partitioning the material into three sections helps focus each discussion.

2.2.1. SeaWiFS sea truth data accuracy considerations and advancements

Ensuring the SeaWiFS radiometric retrievals of water-leaving radiance are within 5% over the life of the mission requires a continuing commitment to quantifying the uncertainties associated with the spaceborne and in situ instrumentation. This means the individual sources of uncertainty for the acquisition of ground-truth data must be on the order of 1–2%, or what is referred to more generally as simply "1% radiometry". The sources of uncertainty for the ground truth part of the total uncertainty budget have a variety of sources:

1. The measurement protocols used in the field;
2. The environmental conditions encountered during data collection;
3. The absolute calibration of the field radiometers;
4. The conversion of the optical measurements (in-water and above water) to geophysical parameters, e.g., diffuse attenuation and water-leaving radiances, used in a data processing scheme; and
5. The stability of the radiometers in the harsh environment they are subjected to during transport and use.

The SeaWiFS CV element has sought to systematically identify and quantitatively address as many issues associated with all five sources of uncertainty as was fiscally feasible. These efforts are outlined below.

For the SPO, the first step in the process of controlling uncertainties in field data was establishing, through consensus at a community workshop, and then publishing the SeaWiFS Ocean Optics Protocols (Mueller and Austin, 1992). The protocols are a work in progress and and were initially revised in Mueller and Austin (1995), but, under the SIMBIOS program, have undergone substantial expansions (Mueller, 2000, 2002, 2003) by having the scientific community decide which scientific areas would be updated. The SPO has continually used the protocols as the requirements for all ground-truth observations.

The uncertainty in calibrations is the most fundamental, because all the others are only quantifiable if the radiometers are properly calibrated. To maintain internal consistency between calibrations of the in situ sensors (and the SeaWiFS instrument itself), the SPO required calibration traceability to the National Institute of Standards and Technology (NIST) and implemented an ongoing series of SIRREX activities to investigate and minimize calibration uncertainties. In the progression from the first to the third SIRREX (Mueller, 1993; Mueller et al., 1994, 1996; respectively), uncertainties in the traceability to NIST for intercomparisons of spectral lamp irradiance and sphere radiance improved from 7–8% to 1–2%. The fourth through sixth SIRREX activities further investigated laboratory and field protocols (Johnson et al., 1996, 1999a, b; and Riley and Bailey, 1998, respectively), and showed that calibrations at an uncertainty level of approximately 2% were routinely achievable if the ocean optics protocols were carefully implemented. This culminated in a detailed experiment to quantify many sources of uncertainties not thoroughly investigated during previous activities at a single (commercial) calibration facility (Hooker et al., 2002a). Subsequent calibration experiments have been supported by the SPO (Zibordi et al., 2002a) and the SIMBIOS program (Meister et al., 2002, 2003).

One of the original concepts to be tested in the SIRREX activity was to verify the sources and calibration setup 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 SeaWiFS Transfer Radiometer (SXR) was designed and built by NIST as part of an Interagency Agreement with the SPO. The SXR has been proven to be a reliable transfer radiometer, with an uncertainty at all measurement wavelengths of approximately 1.5% (Johnson et al., 1998a). After repeated use in SIRREX activities, the SeaWiFS calibration, and an international integrating sphere comparison (Johnson et al., 1997), the SXR was commercialized in limited numbers and different versions of the same design are being used in other round-robin activities supported by SIMBIOS (a continuation of SIRREX) and the NASA EOS calibration program.

Instrumental drift due to filter deterioration and physical stresses, which can cause shifts in the optical alignment and electrical characteristics of a device, must be quantified even if a concerted effort is made to minimize these problems. To address this problem, NIST was contracted to jointly develop a highly stable portable field source, the SeaWiFS Quality Monitor (SQM; Johnson et al., 1998b; Hooker et al., 1998). Prior to the field commissioning of the original SQM, many aspects of sensor performance were maintained by the instrument manufacturer and were not routinely measured by the individual investigator. The first operational deployment of the SQM demonstrated the importance of independent evaluations of commercial equipment. During that deployment, large changes in the responsivity of some of the radiometers (as much as approximately 25% over a 1 month period) were detected (Hooker and Aiken, 1998). The SQM has a demonstrated capability of monitoring the stability of light sensors to within 1% in the field (Hooker and Maritorena, 2000) and was sufficiently successful to be commercialized by two different companies (Hooker, 2002).

Regardless of the performance of an instrument in the field, the absolute characterization of a sensor in the laboratory is the starting point for almost all other subsequent evaluations. After the conclusion of investigating uncertainties in radiometric calibrations, the immersion factors of irradiance sensors were investigated during SIRREX-8 (Zibordi et al., 2002a), and were found to be a significant source of uncertainty (more than 10% in the blue domain, and approximately 2–6% in the green and red regions). The activity also showed it was possible, however, to maintain a 1%

uncertainty budget for characterizing immersion factors (Zibordi et al., 2004a), especially with new protocols based on a smaller laboratory apparatus and more time efficient procedures (Hooker and Zibordi, 2003a). In particular, the Compact Portable Advanced Characterization Tank (ComPACT) method, which uses a very small water vessel (3 l versus as much as 3000 l for traditional methods) provides the significant advantage of a quality-assured and reproducible volume of pure water (Zibordi et al., 2003).

The uncertainties associated with data processing are tied to the protocols, but there are subjective aspects, like the choice of the in-water extrapolation interval, which are not completely resolved by a single protocol. The first SeaWiFS Data Analysis Round Robin (DARR-94) investigated data processing uncertainties and showed differences in commonly used data processing methods for determining primary optical parameters from in situ light data were about 3–4% of the aggregate mean estimate (Siegel et al., 1995). These results applied primarily to Case-1 waters, but issues in turbid waters remained. The focus of the second DARR (DARR-00) was to determine if these results could be improved (Hooker et al., 2001). In terms of overall spectral averages, many of the DARR-00 intercomparisons were to within 2.5%, and if the processing options were made as similar as possible, agreement to within less than 1% was possible.

The optical parameters do not account for all of the validation requirements. For instance, the determination of chlorophyll-*a* concentration is central to the SeaWiFS program pigment objective of agreement to within 35%. An initial intercomparison of four laboratories using four different high performance liquid chromatography (HPLC) methods for determining total chlorophyll-*a* concentration showed the overall accuracy of the four methods in predominantly mesotrophic waters was within 8% (Hooker et al., 2000a, Claustre et al., 2004). Subsequently, a more extensive pigment round robin of US laboratories was conducted by the SIMBIOS Project (Van Heukelem et al., 2002) and an international round robin jointly supported by the SeaWiFS and SIMBIOS Projects is underway (Hooker et al., 2003a).

2.2.2. Field instrument development and evaluation

Although the original calibration and validation planning did not consider instrument technology development, the limitations of the existing commercial laboratory and field radiometers and instrument monitoring devices for ocean-color remote sensing applications became apparent fairly early in the program. As a result, the CV element began investing in instrument evaluation in an effort to accelerate instrument design improvements and to identify subtle problems in instrument performance and characterization. This activity is closely tied to the calibration round robin and measurement protocol activities. For example, the results of SIRREX-8 showed that the immersion factors supplied by a commercial manufacturer were more than 10% in error at some wavelengths (Zibordi et al., 2002a), and there are other examples of the need for independent confirmation of performance specifications in the literature (e.g., Mueller, 1995, Hooker and Maritorena, 2000).

This activity has led to several improved designs for both above- and in-water measurements. Fig. 4 is a mosaic of some of these instruments, and Table 2 provides information on the progression of designs for both types. In each case, the basic strategy was to move toward smaller instrument packages and improved radiometric performance and measurement configuration knowledge. Also, for the in-water measurements, higher vertical resolution and smaller size was a goal, so the instruments could be used in more turbid waters where vertical gradients and instrument self-shading can be problematic. For example, in the progression from the LoCNESS to the microNESS, the in-air weight was reduced by almost a factor of 6, the cross-sectional area was reduced by almost a factor of 2, and the full-scale depth accuracy was improved by a factor of 25. The microNESS and microSAS instruments now provide highly accurate measurements of L_{WN} and remote sensing reflectance (R_{rs}) in Case-1 and Case-2 waters from any standard deployment platform. Furthermore, as a result of rigorous refinements to above-water measurement protocols, recent comparisons of above- and in-water measurements no longer differ by a methodological bias—they agree to within the uncertainty in calibrating the radiometers (Hooker et al., 2003b, Zibordi et al., 2004b).

2.2.3. The SeaWiFS project field program

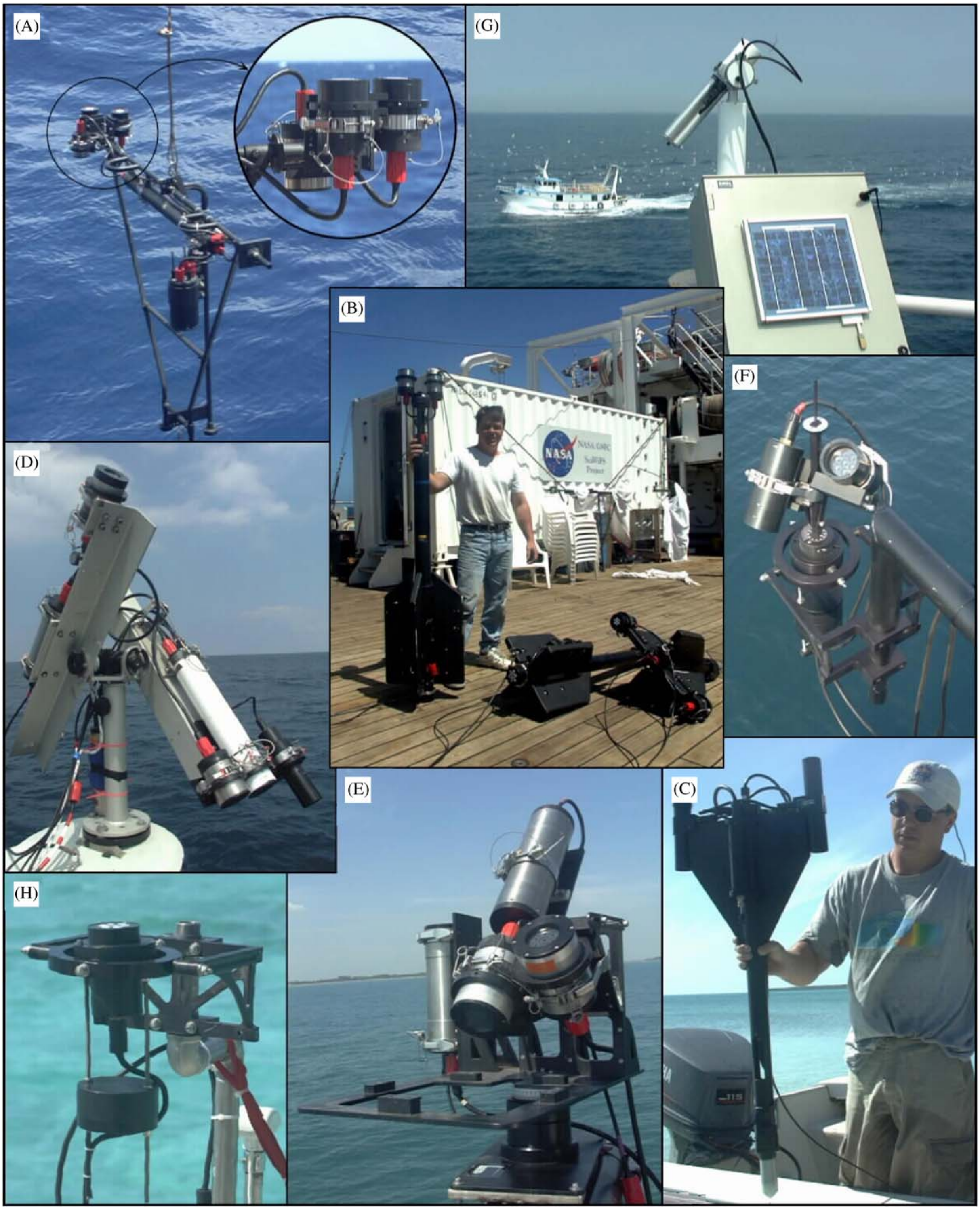
The instrument development and evaluation activities and measurement protocol experiments discussed above were linked to an extensive field program. The field program revolved around three primary sets of field studies (collaborations). These were the British Atlantic Meridional Transect (AMT; Aiken et al., 2000) program (Plymouth Marine Laboratory), studies from the *Acqua Alta* Oceanographic Tower (AAOT) in the Northern Adriatic Sea (the Joint Research Center, JRC, in Ispra, Italy), and various cruises in the Mediterranean Sea, northwest African upwelling, and South Africa (Laboratoire d'Océanographie de Villefranche, LOV, inVillefranche-sur-Mer, France). Each collaboration was formalized with a Letter of Agreement (LOA) between NASA and the international institution. Table 3 provides a summary of the major field campaigns in which the SPO participated.

The AMT cruises took place on board the Royal Research Ship *James Clark Ross* when it steamed between England and the Falkland Islands in support of British Antarctic Survey (BAS) activities in the Southern Hemisphere. The odd-numbered, southbound cruises sampled the boreal autumn and austral spring; while the even-numbered, northbound cruises sampled the boreal spring and austral autumn. Because of the geographic extent of the transects (more than 100° of latitude and 50° of longitude), the repetitive scheduling of the cruises (two per year lasting more than 30 days each), the diversity of the environments encountered (oligotrophic gyres to upwelling zones and eutrophic coastal regions), along with the use of the newest radiometer designs (including calibration monitoring in the field with the SQM), the AMT Program was a particularly timely and substantial accomplishment. Deployments on the AMT cruises were greatly simplified by having the SeaWiFS Portable Laboratory secured to the deck during the operations and stored either in the UK or the Falkland Islands between deployments. The SPO also provided a conductivity–temperature–depth (CTD) system with 30 l bottles to allow sufficient water collection in highly oligotrophic waters, which was used on four of the first nine cruises from September 1995 to June 1999.

The AMT optical experiments were designed to compare a variety of deployment techniques used to measure the in situ light field and to incrementally improve the methods and instrumentation employed. Both above- and in-water sensors and methods were evaluated during AMT cruises, but the latter constituted the majority of the effort. The culmination of the in-water experiments was a demonstration that the in situ part of the SeaWiFS uncertainty budget (3.5%) could be satisfied with a dedicated effort of recurring calibrations, stability monitoring, and strict adherence to the ocean optics protocols (Hooker and Maritorena, 2000).

Field experiments with the JRC were conducted at the AAOT, which is located approximately 15 km southeast of the city of Venice in the northern Adriatic Sea. The potential for using oceanographic towers, as an alternative to buoy or shipboard measurements, for ocean-color calibration and validation activities is being realized at the AAOT (Zibordi et al., 1995). If the observations are periodic (monthly), short deployments are easily accomplished with the former (Zibordi et al., 2002b), and if a modular in-water system that allows the removal of the light sensors in between measurement campaigns is used, the most difficult aspect of moored systems—bio-fouling of the in-water optical sensors—can be completely eliminated and a high-quality time series can be produced (Berthon et al., 2002).

Towers and research vessels are necessarily large structures, and the primary advantage of the former over the latter is stability. Optical instruments can be deployed on a tower with virtually no tilt and the solar illumination geometry, which is needed for an accurate removal of superstructure shading effects on in-water measurements (Zibordi et al., 1999; Hooker et al., 2002b; Doyle et al., 2003), can be accurately determined. The stability and absence of in-water data degradation (no bio-fouling plus the use of in-water correction schemes for perturbative effects or easily implemented avoidance metrics for above-water measurements)


(A)
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NASA

makes AAOT deployments excellent opportunities for above- and in-water intercomparisons to examine many different aspects of measurement protocols. A 1 year intercomparison of water-leaving radiances derived from SeaPRISM and an in-water system, for example, showed the overall spectral agreement was within 10% in the blue–green channels (Zibordi et al., 2002c). Recent improvements in the above-water methodology that incorporate bidirectional corrections and a more accurate modeling of the surface reflectance (Hooker et al., 2003b), however, show a time series of data can be constructed using an autonomous above-water system that has an uncertainty in keeping with calibration and validation uncertainties (Zibordi et al., 2004b).

Additional field campaigns conducted with the Laboratoire d'Océanographie de Villefranche have included the *Productivité des Systèmes Océaniques Pélagiques* (PROSOPE) deep-ocean cruise to the Mediterranean Sea and the northwest African upwelling plus a satellite calibration cruise to the Benguela Current off South Africa (called BENCAL; Barlow et al., 2003). In addition, the SeaWiFS and SIMBIOS Projects have contributed to the development of a new type of optical buoy called *Bouée pour l'acquisition de Séries Optiques à Long Terme* (BOUSSOLE), which was operationally deployed in the Ligurian Sea between France and Corsica, and is based on commercial-off-the-shelf sensors (Antoine and Guevel, 2000).

Combining the careful metrology established during AMT cruises with the unique and well-established capabilities of the LOV and JRC groups resulted in several additional noteworthy accomplishments:

1. Zibordi et al. (1999) measured the shading induced on in-water optical measurements by a large offshore tower and developed a correction scheme for the in-water sensors.
2. Claustre et al. (2002) demonstrated that Saharan dust deposition reduced blue reflectance and enhanced green reflectance causing anomalously high chlorophyll retrievals.
3. Hooker and Morel (2003) quantified ship reflectance contamination in above-water measurements and outlined measurement protocol and quality control procedures for retrieving data accurate to within 5%.
4. Hooker et al. (2002b) conducted the first rigorous comparison of above-water measurement and in-water measurement methods. The overall intercomparison of all methods across Case-1 and Case-2 conditions was at the 9% level for the spectral averages.
5. Hooker et al. (2003c) mapped the effect of an offshore tower on the above-water method and established sampling metrics to prevent data degradation (Hooker and Zibordi, 2003b). If the sampling metrics are combined with the Hooker et al. (2003b) methodology, the above- and in-water determinations of water leaving radiances converge to within the total uncertainties in the methods, about 3% (ignoring environmental variability).

In addition to improving the radiometric reliability and accuracy of the optical instrumentation, the development process greatly increased the amount of data collected during the field campaigns. For example, if the off-the-shelf approach of AMT-1 is used as a reference, there was approximately a 100% increase in the number of radiometric profiles collected during AMT-3, a 600% increase during AMT-5, and a 900% increase during AMT-7. Some of these increases were the result of efficiencies that are always

Fig. 4. A collage of the primary above- and in-water optical instruments developed to support SeaWiFS calibration and validation field campaigns: (A) SeaOPS (the inset magnification shows the orientation of the three optical sensors); (B) THOR (held upright) with LoCNESS and miniNESS (on deck) in front of the SeaWiFS Portable Laboratory; (C) microNESS being operationally deployed for the first time from a very small (less than 5 m long) boat; (D) SeaSAS configured to permit the intercomparison of three different above-water sensor designs (including the prototype microSAS sensor); (E) SUnSAS with the DIR-10 (directional) unit (the vertical, leftmost cylinder) and the viewing aperture open (a 25.4 cm plaque can be fitted into the aperture to allow for alternative measurement protocols); (F) microSAS fitted inside a cardanic gimbal and mounted at the end of an extensible deployment system built at the JRC; (G) SeaPRISM being operationally deployed at the AAOT after 1 year of field testing by the JRC; and (H) field testing of the first gimbaled solar irradiance reference on a very small boat.

Table 2
Summary of field instruments developed with support of the SeaWiFS calibration and validation program

Instrument	Characteristics	References
In-water optical instruments		
SeaWiFS Optical Profiling System (SeaOPS)	• $L_u(z,\ddot{e})$, $E_d(z,\ddot{e})$, and • $E_s(0^+,\ddot{e})$, initially • $E_u(z,\ddot{e})$ added later • Winch and crane system (for large ships and platforms) with 16-bit analog-to-digital (A/D) conversion	Robins et al. (1996) Aiken et al. (1998) Hooker and Maritorena (2000)
SeaWiFS Free-Falling Advanced Light Level Sensors (SeaFALLS)	• Free-falling, 24-bit A/D conversion, integral unit (not modular)	Aiken et al. (1998) Hooker et al. (1999) Hooker and Maritorena (2000)
SeaWiFS Square Underwater Reference Frame (SeaSURF) and the SeaWiFS Buoyant Optical Surface Sensor (SeaBOSS)	• Two different surface reference systems that can be floated away from a platform	Aiken et al. (1998) Hooker and Lazin (2000) Hooker and Maritorena (2000)
Low-Cost NASA Environmental Sampling System (LoCNESS)	• Same as SeaFALLS, but with cheaper components (16-bit A/D) and modular	Aiken et al. (1998) Zibordi et al. (1999) Hooker et al. (1999) Hooker and Maritorena (2000)
THOR	• $L_u(z,\ddot{e})$, $E_d(z,\ddot{e})$, $E_u(z,\ddot{e})$ • Longer than SeaFALLS • Built for Q-factor studies	Hooker et al. (1999) Hooker and Lazin (2000) Barlow et al. (2003)
miniNESS	• Smaller than LoCNESS • Suitable for small boats	Hooker et al. (1999) Hooker et al. (2000b) Doyle et al. (2003)
microNESS	• Smaller than miniNESS • Suitable for moderately turbid and shallow water • Digital interfaces	Hooker et al. (2003c) Barlow et al. (2003)
Above-water optical instruments		
SeaWiFS Surface Acquisition System (SeaSAS)	• Suitable for platforms and large ships • Manual pointing	Hooker et al., 1999 Hooker and Lazin (2000) Hooker et al. (2002b)
SeaWiFS Shadow band (SeaSHADE)	• Rotating shadow band sun photometer for attachment to irradiance reference sensors	Hooker and Lazin (2000) Hooker et al. (2003c)
SeaWiFS Underway Surface Acquisition System (SUnSAS)	• Suitable for platforms and small ships • Manual pointing	Hooker and Lazin (2000) Hooker et al. (2000b) Hooker and Morel (2003)
Micro Surface Acquistion System (microSAS)	• Suitable for very small ships • Gimbaled to reduce platform motion	Hooker et al. (2003b) Hooker et al. (2003c) Hooker and Zibordi (2003b)
SeaWiFS Photometer Revision for Incident Surface Measurement (SeaPRISM)	• Stable platforms only • AERONET compatiblewith automated satellite data transmission	Hooker et al. (2000b) Zibordi et al. (2002c) Zibordi et al. (2004b)

The listings under the in-water and above-water categories are in chronological order and represent systematic improvements in radiometry, reductions in size, and, for the above-water instruments, more accurate pointing knowledge. The in-water systems measure upwelling radiance ($L_u(z,\lambda)$), downwelling irradiance ($E_d(z,\lambda)$), and downwelling surface irradiance ($E_s(0^+,\lambda)$, separately). The Three-Headed Optical Recorder (THOR) includes upwelling irradiance ($E_u(z,\lambda)$). The above-water instruments measure surface upwelling radiance and sky radiance.

Table 3
A summary of the major deep ocean and coastal field campaigns directly supported by the SPO

Campaign	Investigator(s)	Dates	Stations
AMT-1	S. Hooker and G. Moore	Sep.–Oct. 1995	25
AMT-2	G. Moore and S. Hooker	Apr.–May 1996	24
AMT-3	S. Hooker, J. Aiken, and S. Maritorena	Sep.–Oct. 1996	30
AMT-4	S. Hooker and S. Maritorena	Apr.–May 1997	56
AAOT	S. Hooker and G. Zibordi	July 1997	6
AMT-5	S. Hooker, J. Aiken, and S. Maritorena	Sep.–Oct. 1997	47
AMT-6B	G. Moore, S. Hooker and S. Maritorena	Apr.–May 1998	30
AMT-6	S. Hooker, J. Aiken, and S. Maritorena	May–June 1998	61
SeaBOARR-98	S. Hooker and G. Zibordi	July 1998	6
AMT-7	S. Hooker, J. Aiken, and S. Maritorena	Sep.–Oct. 1998	57
AMT-8	S. Hooker and S. Maritorena	May–June 1999	52
SeaBOARR-99	S. Hooker and G. Zibordi	August 1999	4
PROSOPE	S. Hooker, A. Morel, and S. Maritorena	Sep.–Oct. 1999	21
Coastal-1	S. Hooker and J. Brown	Feb.–Mar. 2000	17
SeaBOARR-00	S. Hooker	Apr.–May 2000	30
ADRIA-2000	S. Hooker, J-F. Berthon, and G. Zibordi	July 2000	55
Coastal-4	S. Hooker and J. Brown	Feb.–Mar. 2001	29
SeaBOARR-01	S. Hooker and G. Zibordi	June 2001	18
BOUSSOLE	S. Hooker and D. Antoine	July 2001	7
SeaBOARR-02	S. Hooker and G. Zibordi	June 2002	15
BENCAL	S. Hooker, J. Brown, J. Aiken, and A. Morel	October 2002	42

The SeaWiFS Bio-Optical Algorithm Round Robin (SeaBOARR) campaigns are associated with the general problem of investigating how methodological factors influence the data used in bio-optical algorithms.

gained from repeating any exercise over and over again, but the majority were the direct consequence of modifying the equipment and methods used. These modifications included a custom-built data acquisition capability to permit the rapid collection of radiometric data from the simultaneous deployment of multiple instruments.

2.3. Data processing system

The design of the SeaWiFS data processing system (SDPS) incorporated many of the lessons learned during the development and operation of the CZCS global reprocessing (Feldman et al., 1989). The initial design was a close collaboration between the SPO and the University of Miami Rosenstiel School for Marine and Atmospheric Sciences (RSMAS), with the invaluable technical support from Silicon Graphics Incorporated (SGI). By designing the system to satisfy a number of well-specified requirements and through a process of rapid prototype development and extensive testing, and new technology evaluation, the system has been continually modified to handle additional requirements (i.e. new products, algorithm refinements, increased data volumes, and new satellite missions) while also improving the system's capability to meet the operational mission requirement without requiring additional budget supplements over what had originally been requested.

The original objective was to have an ability to process 10 times the received data volume so as to have the ability to reprocess the entire data set within a reasonable amount of time without affecting operational processing. As mentioned earlier, the original SPO-wide computing design was three Unix servers connected to X-terminals. Even during the prelaunch phase, this strategy proved inadequate to meet the computational requirements and the SPO replaced the X-terminals with workstations. The approached worked very well, but was expensive in terms of hardware and maintenance. Since launch, relatively inexpensive, yet powerful, PC-based Linux systems have emerged and are systematically replacing the staff's workstations . The Linux systems are also being clustered to augment the Unix servers to increase overall operational processing throughput as HRPT station data volume and calibration and validation evaluation processing requirements grow. In addition, process-control software has evolved from relying solely on the central servers to being able to utilize all computer resources within the SPO.

The original products to be derived from the raw data stream (Darzi, 1998) included navigated calibrated radiances (level-1), derived geophysical products (level-2; normalized water leaving radiances, chlorophyll-*a*, CZCS pigment, diffuse attenuation at 490 nm, and certain atmospheric parameters), binned products on a fixed grid (level-3), and standard mapped products. Level-2 products included a number of masks and flags that are used to identify pixels that are not processed (e.g., clouds) or indicate some special circumstance, e.g., shallow water (McClain et al., 1995). The mask and flags are incorporated in the level-2 products and can be individually displayed. Some flags are used as exclusion criteria for level-3 binning. Changes in the product suite and the masks and flags have been instituted at various reprocessings. For example, the CZCS pigment product has been discontinued, and PAR and NDVI have been added. Also, after the third reprocessing, a set of evaluation products, e.g., CDOM, were included in the routine processing stream in collaboration with the scientists outside the SPO. Evaluation products are displayed on an evaluation product Web site for consideration by the community. Once the community expresses sufficient interest in a product, it is graduated to archive product status as was done with PAR. NDVI is supplied to a terrestrial research group at GSFC who quality control the product before sending it to the DAAC.

Because the SDPS was designed from the very start to be a thoroughly integrated component of the SPO, driven by science, data quality and data availability considerations (essentially a bottoms-up approach designed by scientists for scientists) rather than by a more computer and information system approach, i.e. a top-down approach. The DP element has to interact with a large number of groups to be able to carry out its functions. Some of these are internal to the SPO (i.e. the other elements), some internal to NASA, but physically separated from the SPO (e.g., DAAC, WFF) and others often halfway around the world, such as the remote HRPT receiving stations that collect and provide the SPO with copies of the SeaWiFS data they receive.

2.3.1. System requirements

The five key functions that drove the design of the SDPS required that the system are the following:

Process large volumes of data in a timely fashion. By using realistic estimates of processing/reprocessing rates, data handling requirements, and through very extensive simulation of actual end-to-end system operations, potential bottlenecks in system throughput were identified and corrected prior to launch. The products and their volumes were known and used in the system design. The instrument- and spacecraft-driven delays in launch were taken advantage of by the SPO to simulate full mission functions from downlink to DAAC distribution, day in and day out for at least one full year before launch. The end-to-end testing was possible because the MO element generated simulated level-0 data sets (Gregg et al., 1994). It cannot be overemphasized how absolutely critical the comprehensive prelaunch system tests were to the generation of credible level-1, -2, and -3 products on the first day of routine operations.

Require as little human intervention as possible. While the interactive quality control of each and every SeaWiFS data product was a key design requirement, the interaction between the software developed by the CV group to perform the quality control and the DP element to deal with the outcome of that process was optimized through the use of shared database tables and procedures. Because the SPO had decided very early in the planning process to maintain its own archive of the complete mission data (in this case both level-0 and level-1a), algorithm testing on large data sets, product validation subscene extractions, and reprocessings could proceed without many of the coordination issues that have impeded other larger and more complex missions.

Allow changes to the processing methods to be easily implemented. By acknowledging that as understanding of the instrument and the science improves, there will be a need to modify the algorithms and processing procedures, and the system should be able to accommodate these changes in a straightforward manner without affecting the operational processing. By designing the system to have parallel development and operational environments, changes to the system procedures could be easily implemented, thoroughly tested and evaluated, and migrated into production with minimal impact.

Permit multiple processing streams. It is completely unrealistic to design a satellite data processing system without providing for the concurrent processing of multiple streams of data. For the SDPS, the system was scoped for a minimum of at least three simultaneous and concurrent processing streams for real-time operational processing, complete mission reprocessing, and development and testing processing. This analysis resulted in a design goal of being able to have a $10\times$ overall system capacity (process ten days of global data per day).

Be easily understood and documented. Most interactions with the SDPS are carried out through a series of simple graphical user interfaces (GUI) that interact directly with the various databases that control all system functions so that even very complex procedures such as redefining how a data file should be processed, what data products are to be produced, and at what step in the processing each data granule resides at any moment is a relatively simple, and easy to manage task. Extensive Web-based documentation of all key system components, public access to most system source code, and a complete, online log of system-related updates make the SDPS a very open, easily understood system. As a demonstration of this, the entire SDPS has been ported to at least two other groups (National Oceanic and Atmospheric Administration and MODIS) to serve, in NOAA's case, as an operational system to process Ocean-color and Temperature Scanner (OCTS) data and for MODIS, as a prototype data processing system to demonstrate the ability to process MODIS data outside of the Earth Observing System (EOS) Distributed Information System (EOSDIS) Core System (ECS).

2.3.2. System design

The design philosophy that was used to develop the SDPS was quite different from most other major satellite missions. Once a top-level system requirement was identified, rapid prototyping of basic core functions was used to develop the key components of the SDPS. Once the prototype function had enough capability to be tested, a comprehensive evaluation of it was carried out, strengths and weaknesses were identified, and refinements were made to eventually converge on a final implementation. As a result, the functionality developed at the very beginning of the SeaWiFS program evolved over time to incorporate a wide range of additional requirements. The four major components of the SDPS are the (1) database, (2) the Services Layer, (3) the Scheduler, and (4) the Visual Database Cookbook (VDC).

The heart of the SDPS is a relational database management system (RDMS), which provides all the controlling, scheduling, and cataloging functions for the system. The SDPS uses a commercial off-the-shelf software (COTS) standard query language server (Sybase), but any RDBMS can be used because of the system's database Services Layer, which contains all the vendor-specific database functions. If it were decided to use another RDMS, only the Services Layer would need to be updated because it shields all the other system functions from any RDMS-specific dependencies. There are two types of databases within the SDPS: core databases and mission-specific databases. The core databases support the processing, cataloging, and administration functions within the SDPS, while the processing database's primary function is to provide controlling and scheduling functions for the SDPS.

For scheduling, a table called *todolist* is used. This table contains records that describe jobs (tasks) that need to be done for the current day.

The task's attributes define the characteristics of the job such as its type, when it should be run, which machine it should run on, and its status. Tasks can run at set intervals of time (monitor tasks), at a specific time (timed tasks), or be triggered by some event (triggered tasks). The Scheduler monitors the records in the *todolist* table, and submits jobs to the operating system at the appropriate time. When a task completes, successfully or unsuccessfully, it records its status in the *todolist* table. At any point, a new task can be added, unwanted tasks suspended or deleted, or tasks rescheduled through the Task Editor GUI. Tasks not completed on any given day may be rolled over to the next day when the system reconfigures itself each night at midnight. For instance, data transfers between remote receiving stations and the SPO can often take several hours depending on the network links, so tasks not completed at midnight are carried over and show up on the next day's *todolist*.

This scheme works well for high-level tasks and simple processing, but for low-level, complex processing (multi-step processing of SeaWiFS data from level-1 through level -3 for example) , the VDC is more suitable. When a file is queued for VDC processing, a new record is inserted into one of the processing control database tables (the "activeproc" table) where it waits in line until all of the ancillary data needed for processing have been identified and staged. Once this occurs, the file is admitted into the VDC and passed along to any of the system resources available for processing. One of the key design features of the SDPS is its distributed processing environment with system allocation of any/all available resources ranging from a multiprocessor SGI to desktop Linux machines. The system is scalable in size and is able to take advantage of resources as needed. For instance, many of the desktop machines used by SPO staff are available for processing when either the load on them is sufficiently low or when they have been idle for a predetermined amount of time. A simple entry in one of the database tables can add or remove these resources from the available pool.

The VDC uses two abstract concepts: a virtual computer processing unit (CPU) and a recipe. A virtual CPU is a work space defined on a machine that can be used by the VDC. This work space is one or two directories, defined as input and output buffers, which will contain all of the files needed and produced by the individual steps of the processing. The work spaces are defined in the hosts and resources tables and are allocated and freed automatically by the VDC. Depending upon the capabilities of each computer defined as a resource, multiple virtual CPUs can be allocated on any given machine. Currently, the SPO has approximately 90 virtual CPUs to call on to meet its processing needs, although the actual number of computers is significantly less. There are three basic functions associated with the VDC: Entrance, Master, and Exit. The Entrance program is the entry point into the VDC, and it monitors the entrance directory for new data to process, allocates the necessary resources, reads the job command file, stages the data for processing, and creates a stream record that signals the VDC to begin automatic processing. The Master program is, in a sense, the master chef for the VDC. It monitors the Streams table for stream records that are ready to be processed, marks them as busy, and invokes the processing jobs according to the steps of the assigned recipe. Essentially, it moves a job from one step to the next until it is completed. The Exit program is the final stage of the VDC. It monitors the Streams table for stream records that have completed processing, de-allocates the resource making it available for another job, records the completion time, deletes the input data file, and marks the stream record ready for deletion.

A recipe is a processing scheme that consists of a set of steps, each step performing a separate task. The VDC invokes the steps sequentially, just as a chef would follow a cooking recipe. The recipes are defined in the "recipe_lookup" and recipes tables. Because the recipe steps are designed to perform as small a set of functions as possible, one step in the recipe table can be used by a large number of different processing scenarios. One step, CPYVDC, does nothing but copy all of the input data files, ancillary files, and parameter files into the processing directory and is used by many different recipes.

2.3.3. System evolution

The design goal of 10 × (for global GAC) processing was met at launch and, through a combination of processor and network speed advances, additional processors (mostly desktop systems), and process control software that dynamically utilizes all available computing resources within the SPO, the system has realized the following throughput improvements: second reprocessing (August 1998), 40 × ; third reprocessing (May 2000), 130 × ; fourth reprocessing (May 2002), 400 × . Recent system benchmarks show a 3000 × throughput which translates to a complete regeneration of all the standard archive products for the entire mission in less than 1 day.

2.4. Data distribution

Under the contract with ORBIMAGE, only authorized SeaWiFS researchers may have access to the digital SeaWiFS data for research and educational purposes, and the SPO is responsible for providing the DAAC with a list of these authorized researchers. During the early part of the SeaWiFS mission, researchers were required to submit a written proposal to the SPO for review, and if the intended use of the data fell within the agreed upon activities outlined in the contract, then that researcher was added to the list and the DAAC was notified. Recently, this process has been streamlined through the provision of an online request form where potential SeaWiFS data users can submit all the required information electronically, and where after review and approval, acceptance messages are passed to the DAAC and to the researcher. This process is generally completed on the same day that the submission is made. While most requests are generally approved, submissions from commercial interests are referred directly to ORBIMAGE. Since launch, there has been an almost constant rate of increase in the number of authorized users, which now exceeds 2300.

The original contract with Orbital Sciences provided NASA with 13 real-time licenses that allowed decryption as the data were received. Aside from the SPO, licenses were distributed to stations in Mississippi, California, Alaska, and Hawaii. These sites could distribute real-time data for validation cruise support with SPO permission. To assist in validation efforts and cruise planning, the SeaWiFS and SIMBIOS Projects jointly developed a real-time user support Web site, which allowed the user community to obtain overflight predictions and real-time data products for cruise support and demonstration studies. As a result, real-time data products have been provided to nearly 400 field campaigns.

Because the SeaWiFS mission was considered to be an early component of EOS, the official data archive and distribution functions were required to be handled by the EOSDIS Version 0 DAAC located at GSFC. The DAAC serves as the long-term archive and distribution facility for all SeaWiFS data once the data has passed the 14-day embargo period, because there is a great deal of valuable science that needs to be conducted using real-time or near-real-time data. In response, the SPO developed an extensive Web-based set of user-friendly browse, order, and image and data distribution tools to service the science community's need for access to this data prior to it being archived at the DAAC. In a typical month, SeaWiFS sends 60–80 gigabytes of compressed data to the DAAC and the DAAC distributes approximately 500–600 gigabytes (compressed volume), or about nine times the archived volume. Acker et al. (2002) provide a comprehensive review of the DAAC's SeaWiFS product distribution statistics.

2.5. Outreach

Outreach has many forms, several of which are mentioned above, e.g., near-real-time support services. Other activities have been focused on simply advertising the SeaWiFS program and the applications of the data. The SPO has worked closely with the GSFC Office of Public Affairs to provide coverage of newsworthy events to the news media. Also, for the first 3 years after launch, the SPO put much emphasis on having a presence at all major Earth science-related conferences (US and international) by providing presentations or an information booth to familiarize different sectors of the potential user community with the mission. Two outreach activities have been particularly important, SeaDAS and the STRS, which are described in detail below.

SeaDAS: One of the lessons learned from the CZCS experience was the need for the user community to have an affordable and easy-to-use data processing capability so that the remote sensing data products could be tailored to their research and applications. Also, having a hands-on capability allows the user to become much more familiar with the processing, helps connect the research community to remote sensing technology and methodologies, and allows the user to integrate alternative algorithms and analysis routines into the software. SeaDAS (Fu et al.,1998; Baith et al., 2001) was an outgrowth of the SEAPAK system (McClain et al., 1991a, b, 1992a) and was designed to meet this need, although it was not considered a project requirement and did not have an explicit budget line. This being the case, it was funded through the NASA Ocean Biogeochemistry Program with assistance (system administration and equipment) from the SeaWiFS and SIMBIOS Projects. This funding supported the SeaDAS staff, which has never exceeded three full-time individuals (usually only two).

SeaDAS development was initiated early on in the prelaunch phase with the first user training classes being held in 1994. SeaDAS is not meant to be a comprehensive analysis system, but is designed primarily to replicate all the operational processing procedures and products (level-0 through level-3; GAC and LAC) while allowing key processing parameters to be varied as the user finds appropriate. To do this effectively, SeaDAS has emphasized product display functionality and diagnostic analyses for evaluating the products. The system initially supported Silicon Graphics and Sun Microsystem Unix workstations and was later adapted to run on PC-based Linux systems. The Interactive Data Language (IDL) is used for the user interface, display functions, map projections, and basic statistical analyses, which allows the software package to be easily expanded by users who write their own IDL routines. A run-time license is provided with SeaDAS for those who do not plan to write IDL routines. SeaDAS is distributed in two forms, compiled executable code and source code. One important benefit from the early prelaunch release of the SeaDAS source code was that it enabled the user community to examine the code and provide feedback to the SPO, e.g, coding errors, and revised or new features. Having the processing flow documented before launch (Darzi, 1998) made the process of reviewing the code much easier. SeaDAS also supports the processing of CZCS, OCTS, Ocean Scanning Multispectral Imager (OSMI), and Modular Opto-electric Scanner (MOS) data, the display of all MODIS oceans products, and the generation of SeaWiFS NDVI fields. SeaDAS has been downloaded to more than 500 unique user sites in over 45 countries since the fourth reprocessing and received the 2003 NASA Software of the Year Award.

SeaWiFS Technical Report Series: Although the CZCS mission and the CZCS global reprocessing effort (Feldman et al., 1989) provided much of the blueprint for setting up the organization and responsibilities of the SPO, most of this important and useful information was outside the subject matter of peer-reviewed publications and was not available in a centralized location, i.e. it was scattered amongst the original participating individuals, institutes, and companies. In some cases, solution processes to important problems were needlessly repeated, because the relevant material, although known to exist, was no longer accessible.

The STRS was created early in the development phase of the SPO to ensure all the scientific, technical, and mission-related accomplishments and approaches were documented and available from at least one source. It also provided a publishing forum for members of the global ocean-color community collaborating with the SPO. The STRS placed a high priority on quality and consistency, and, therefore, standardized document formatting, nomenclature, and symbols. Index volumes were included at regular intervals to include listings of citations, symbols, updates, and corrections. The STRS consists of 43 prelaunch and 29 postlaunch volumes, and has been routinely distributed to nearly 500 scientists, institutes, libraries, and marine information centers throughout the world. In addition, the postlaunch series is available to the general public worldwide as downloadable files from the SeaWiFS Web site (the prelaunch reports are in the process of being converted to downloadable files). Hardcopies of any or all of the pre- and postlaunch series are available upon request from the SPO or the technical editor (Elaine Firestone).

2.6. SeaWiFS reprocessings and data quality improvements

During the first 5 years of SeaWiFS operations, the SPO conducted four reprocessings. These were initiated at the request of the CV element with input from the user community when improvements in the algorithms, field data, or sensor characterization were demonstrated to have a significant effect on data quality. The reprocessings were preceded by extensive analysis and evaluation which was shared with the user community for comment through workshops and Web sites before final approval was given to reprocess. In addition, each reprocessing required considerable coordination between the SPO elements, especially the CV and DP elements, as well as with the DAAC.

The first reprocessing was executed in January 1998, shortly after data acceptance, and incorporated a number of coding error corrections and mask/flag adjustments based on the initial evaluations of the data products. It also included the initial vicarious calibration based on MOBY observations. The second reprocessing was executed in August 1998 after it was determined that significant degradation in the near-infrared (NIR) bands was occurring. The most important improvement associated with the second reprocessing was the use of the monthly lunar images to estimate the time dependence of the sensor sensitivity (Barnes et al., 1999). The third reprocessing was completed in June 2000 and was initiated to address the continuing problem of negative water-leaving radiances in coastal areas. This problem was addressed by including a NIR reflectance adjustment in the atmospheric correction model (Siegel et al., 2000). Also, a new chlorophyll-*a* algorithm that sequenced through a set of three band-ratio relationships, the so-called OC4V4 algorithm, was adopted (O'Reilly et al., 2000). The other major modification in the third reprocessing was the switch to the SPO's code (called MSL12) from the original RSMAS level-2 processing code. Summaries of all the improvements associated with the second and third reprocessings are in McClain et al. (2000b). Finally, the fourth reprocessing was completed in June 2002 (Patt et al., 2003) and incorporated a revised vicarious calibration based on recalibrated data from one of the MOBY systems, which accounted for stray light in the MOBY spectrometer. A subsequent calibration of the second operational MOBY system showed only a slight difference from the values derived for the first system. Also, a revised NIR correction that incorporates the backscattering model of Gould et al. (1999) was adopted. These improvements further reduced the occurrence of negative water-leaving radiances in turbid and coastal waters.

The quality of the data products is evaluated primarily on the comparisons with in situ data (Bailey et al., 2000; Werdell et al., 2003) and L_{WN} stability analyses (Eplee and McClain, 2000). The L_{WN} and chlorophyll-*a* match-up comparisons between the satellite retrievals and in situ data from the fourth reprocessing indicate excellent agreement over the entire range of values for all parameters (Fig. 5). For example, the slope and r^2 for the $L_{WN}(412)$ is 0.992 and 0.82, respectively, for over 200 match ups spanning a range from about 0.1 to nearly 3.0 $\mathrm{mW\,cm^{-2}\,\mu m^{-1}\,sr^{-1}}$. This is particularly important because the atmospheric correction at this wavelength requires the greatest extrapolation from the infrared wavelengths used to select the aerosol model. It is also the most difficult wavelength in the SeaWiFS band set to determine accurate in situ instrument calibrations because of the relatively small standard calibration lamp output. With retrievals of this quality, the 412 nm band can now be used for new applications and algorithms, (e.g., Siegel et al., 2003), especially in coastal waters, e.g., discriminating viable chlorophyll from degradation products (the original purpose for the 412 nm band). For chlorophyll-*a*, the slope and r^2 are 1.03 and 0.85, respectively, for 262 match ups over a range of 0.03 to around 20 $\mathrm{mg\,m^{-3}}$. As a demonstration of

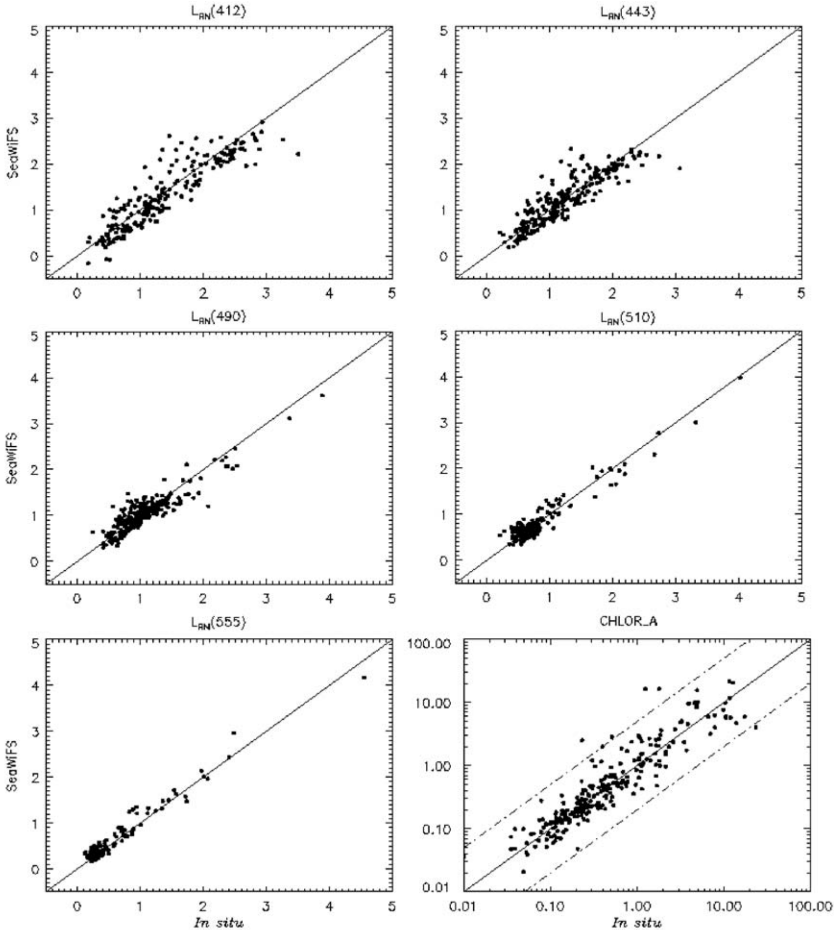

Fig. 5. Comparisons of in situ and satellite L_{WN} and chlorophyll-*a* values, i.e., match-up comparisons, after the fourth reprocessing.

stability, Fig. 6 shows the annual cycles of average deep-water (>1000 m) L_{WN} values for 1998–2003. The plots show that the 510 and 555 nm L_{WN} values are constant and that the 412, 443, and 490 nm L_{WN} values have regular seasonal patterns with little variation from year to year. This stability in the derived products is based solely on the lunar calibrations and is independent of the Earth-viewing data. These results and others are available from the reprocessing Web site and detailed descriptions of the reprocessing and the related analyses are being documented in the STRS.

Finally, assuming the SeaWiFS data buy ends in December 2003, the SPO will conduct a final reprocessing in early 2004. As before, the SPO will solicit the user community's input on algorithm and product improvements, including additional products to be added to the archive product suite.

3. Major geophysical events captured by SeaWiFS

During the first 5 years of global observations, a great many geophysical events have been captured in the SeaWiFS data set. These range from local events such as anomalous phytoplankton blooms (Florida Bay; the southwest Florida Dark Water Observation Group, 2002), volcanic eruptions (Mt. Etna), wild fires (western United States and

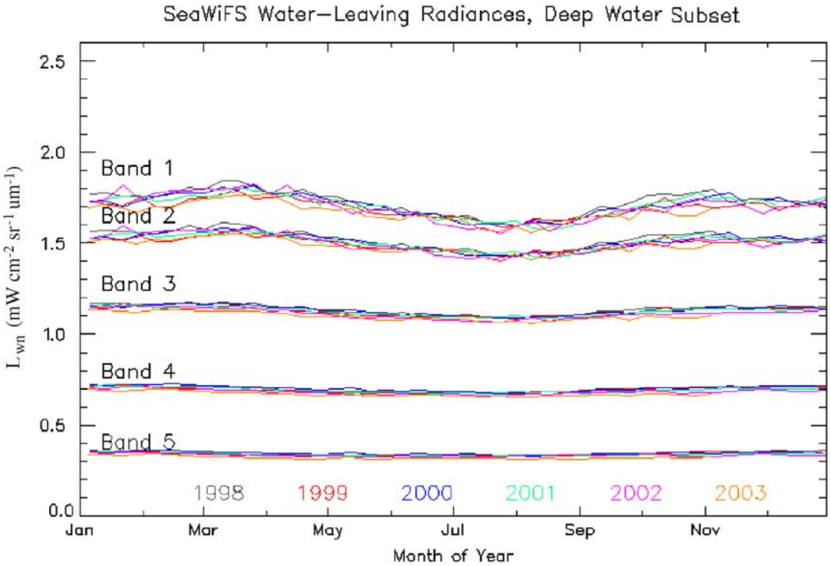

Fig. 6. Comparison of annual cycles of global 8-day mean L_{WN} values for depths greater than 1000 m during the years 1998–2003.

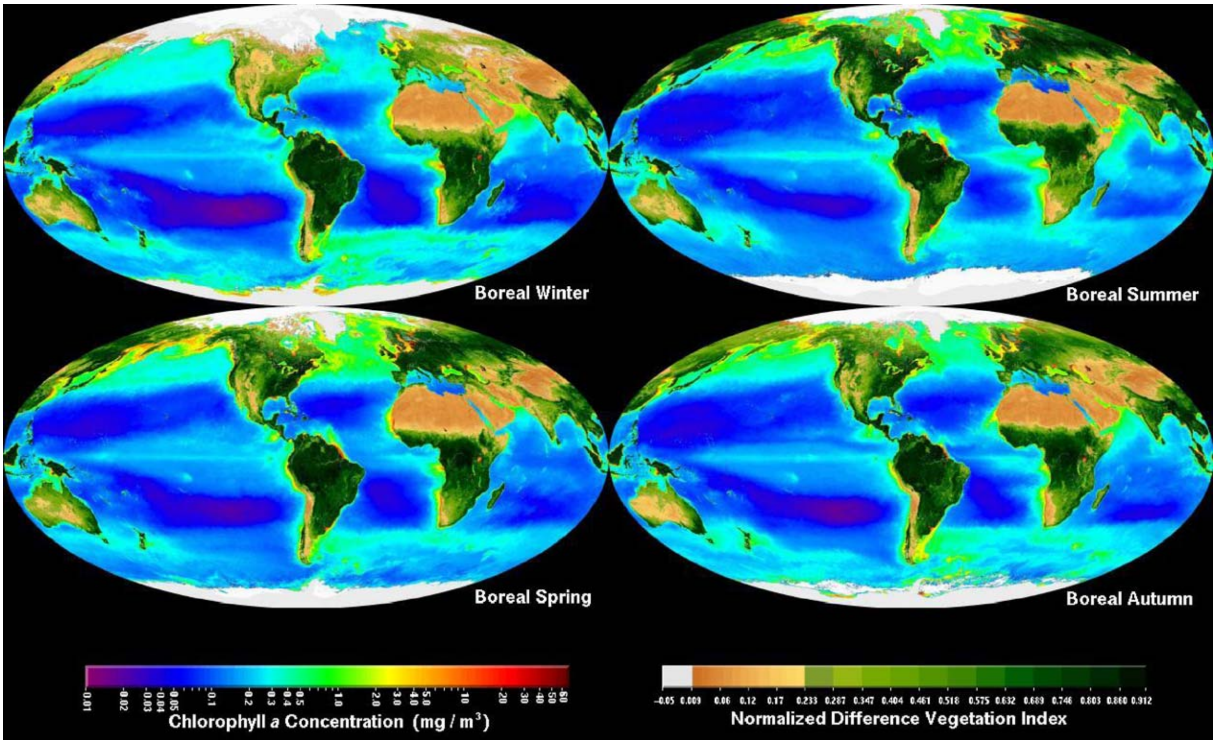

Fig. 7. Global biosphere seasonal cycle. Because SeaWiFS GAC data collection includes all sun lit portions of the orbit, including land masses, it is possible to derive NDVI and other terrestrial products from SeaWiFS. For example, Behrenfeld et al. (2001) generated global time series of marine and terrestrial primary productivity using SeaWiFS data showing that over the first 3 years of data, ocean productivity increased in the post-El Niño ocean, while terrestrial productivity remained constant. This four-panel figure shows the 5-year seasonal climatologies of ocean chlorophyll-*a* and terrestrial NDVI.

Central America), and floods (US mid-Atlantic coast after Hurricane Floyd), to global phenomena such as the 1997–1998 El Niño-La Niña. SeaWiFS data also are being used for freshwater studies, e.g., the Great Lakes (Lesht et al., 2002). Data from the mission have been used frequently by the news media, not only because of its ease of access and rapid turnaround, but also because the SPO and the GSFC Public Affairs staff made it a high priority to provide information on newsworthy events. In this section, an image gallery with brief descriptions (captions) of some of the events of particular interest to the scientific community are provided. Fig. 7 shows the four seasonal climatologies of ocean chlorophyll-*a* and NDVI. Figs. 8–12 are sequenced from local to basin scale events (see figure captions for descriptions). False color images are composed of Rayleigh corrected composites of the 412, 555, and 670 nm SeaWiFS bands.

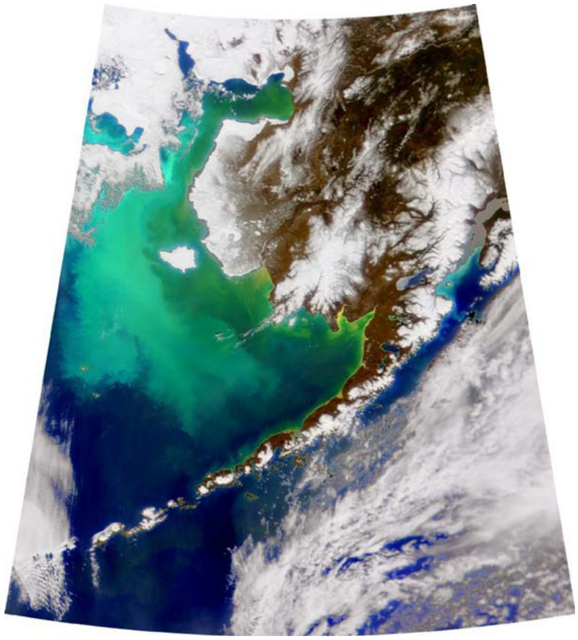

Fig. 8. Bering Sea coccolithophore blooms. During the summer and fall of 1997, a large coccolithophore bloom persisted in the eastern Bering Sea (Vance et al., 1998). Such blooms are very unusual in the Bering Sea and caused widespread starvation of marine birds and mammals and also severely affected fisheries which use the adjacent Alaskan rivers for spawning. The bloom reappeared the following spring and was vividly captured in this 25 April 1998 SeaWiFS image.

4. Summary

SeaWiFS was to be the first in a continuous series of international global ocean-color missions which would provide a high quality climate research quality time series of marine biological and optical properties. Because of the launch slip, OCTS was the first and provided 9 months of global coverage. Fortunately, the SeaWiFS data collection began shortly after the end of the OCTS data record leaving only a 3-month gap. While SeaWiFS was not launched early enough to support much of the JGOFS program, which was a primary rationale for the mission, the 4-year delay did allow the SPO to build much more comprehensive capabilities within each SPO element, which ultimately allowed the SPO to meet its primary goals and objectives early in the program. Additionally, because of its bilinear gain design and accurate calibration, SeaWiFS has proven to be an outstanding tool for terrestrial ecology and aerosol research. SeaWiFS did precede the first MODIS instrument on the Terra platform by 2.5 years and the second on the Aqua platform by nearly 5 years, and was invaluable for MODIS prelaunch preparations and postlaunch validation. SeaWiFS also has served a similar purpose for a number of other ocean-color missions including the European Medium Resolution Imaging Spectrometer (MERIS) and the Japanese Global Imager (GLI). Table 4 summarizes some of the most significant accomplishments of the SeaWiFS program and underscores the point that the program has achieved, even surpassed in most cases, its original objectives and goals.

With support from the SIMBIOS and MODIS programs, the SeaWiFS CV element has undertaken a very comprehensive and coordinated effort, the components of which must be continued in some to-be-determined manner if projects like the NPP/Visible and Infrared Imaging Radiometer Suite (VIIRS) are to provide climate

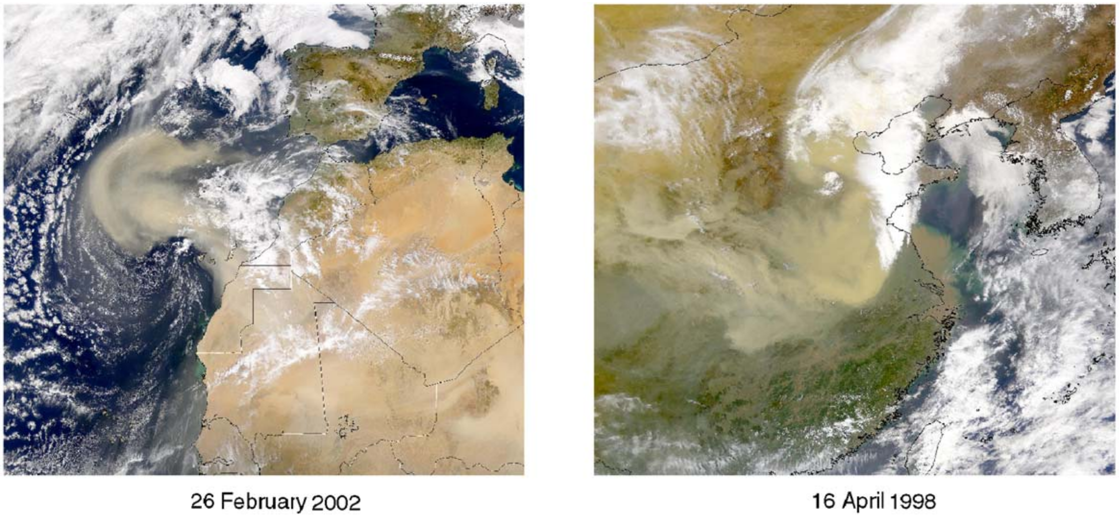

Fig. 9. Asian and Saharan dust events. Because on the bilinear gain design of SeaWiFS, the sensor does not saturate in any of the bands even over the brightest targets. The figure includes examples of dust events off NW Africa (Saharan dust) and over Asia (Gobi dust). Saharan dust has been tracked using SeaWiFS data as far to the northwest as New England. Similarly, Asian dust events have been tracked across the Pacific to the US west coast (Husar et al., 2001). The detection of low levels of dust in the imagery continues to be problematic as it escapes the dust and cloud masks resulting in artificially elevated chlorophyll concentrations.

research-quality data consistent with preceding data sets from SeaWiFS and MODIS. Also, in the future, more emphasis will be placed on providing broader and more accurate suites of products from ocean-color missions for carbon cycle research and coastal zone management, e.g., primary productivity, particulate organic carbon (POC), CDOM, calcite, and total suspended matter (TSM). These will require new or improved algorithms and, in some cases, more accurate atmospheric corrections, especially over turbid water and in areas with absorbing aerosols. More accurate measurements, especially in turbid waters, will be necessary. In addition, some products also may require future missions to make observations further into the ultraviolet where instrument calibration is more challenging. Thus, it is critical that activities such as SeaBASS, the calibration round robin, the protocol development, and the instrument evaluations and development activities be continued after the SeaWiFS and SIMBIOS Projects end.

Finally, the SeaWiFS mission has demonstrated that a data-buy approach to obtaining a science quality data set can succeed, although success does require a determination by both the government and the commercial partners to deliver on their respective obligations no matter how difficult and costly the tasks may be. Success also requires a commitment to work openly and maintain communications no matter how stressful the circumstances may be. Clearly, the numerous technical problems prior to launch and the financial burden on both parties were challenging to bear and both parties had opportunities to terminate the mission. In the end, the resolve was there, solutions were found, SeaWiFS was launched, and the complete data set was delivered. This achievement was recently acknowledged when the SPO and OSC jointly received the prestigious Pecora Award, a joint award from NASA and the Department of Interior, for the mission's contributions to Earth science.

Acknowledgements

The authors acknowledge a number of individuals, groups, and organizations for their

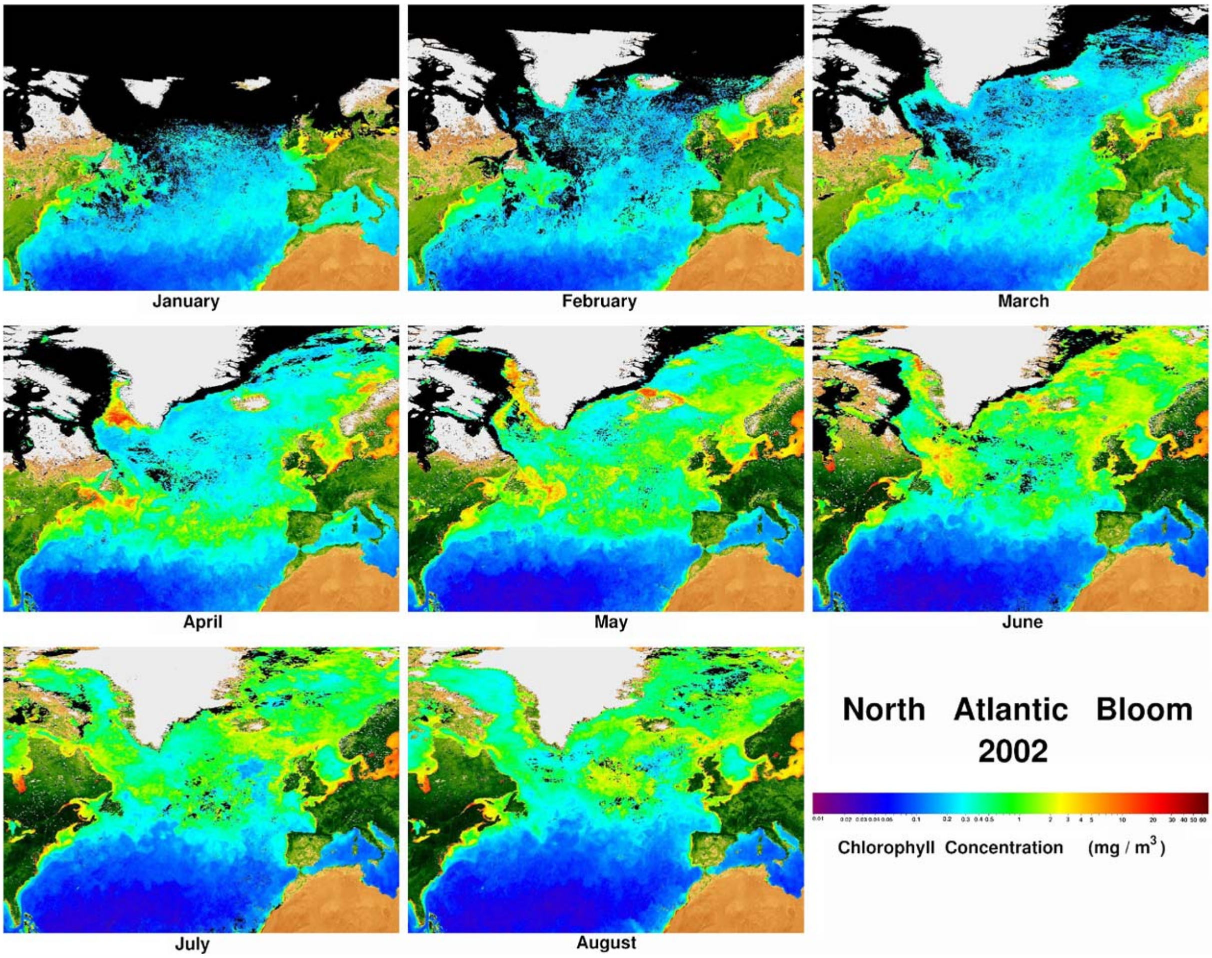

Fig. 10. 2002 North Atlantic spring bloom. Early results from the CZCS global reprocessing highlighted the extent and magnitude of the spring bloom (Esaias et al., 1986; McClain et al., 1990) and the bloom was the subject of the first JGOFS field study. Of the spring blooms observed by SeaWiFS, the 2002 bloom was particularly intense. This sequence of monthly mean chlorophyll composites illustrates the northward migration of the ''green wave,'' a zonal band of high biological production that results as solar illumination increases over the course of spring and summer at higher latitudes.

contributions to the SeaWiFS program. OSC, Santa Barbara Research Center, and ORBIMAGE deserve special recognition for building, launching, and maintaining a spacecraft and instrument that has worked exceptionally well. Several different GSFC engineering groups provided critical assistance to OSC in diagnosing problems with the spacecraft, launch vehicle, and instrument prior to launch. During the prelaunch phase, NASA HQ senior managers, particularly Bill Townsend, Dixon Butler, and Stan Snyder, were steadfast in their support. Throughout the process of getting the mission approved and launched, several Ocean Biogeochemistry Program Managers have assisted and represented the SPO at NASA HQ (Marlon Lewis, Greg Mitchell, Robert Frouin, Jim Yoder, Janet Campbell, John Marra, Chuck Trees, and Paula Bontempi). Science Applications International Corporation (SAIC) and its subcontractors (Science Systems

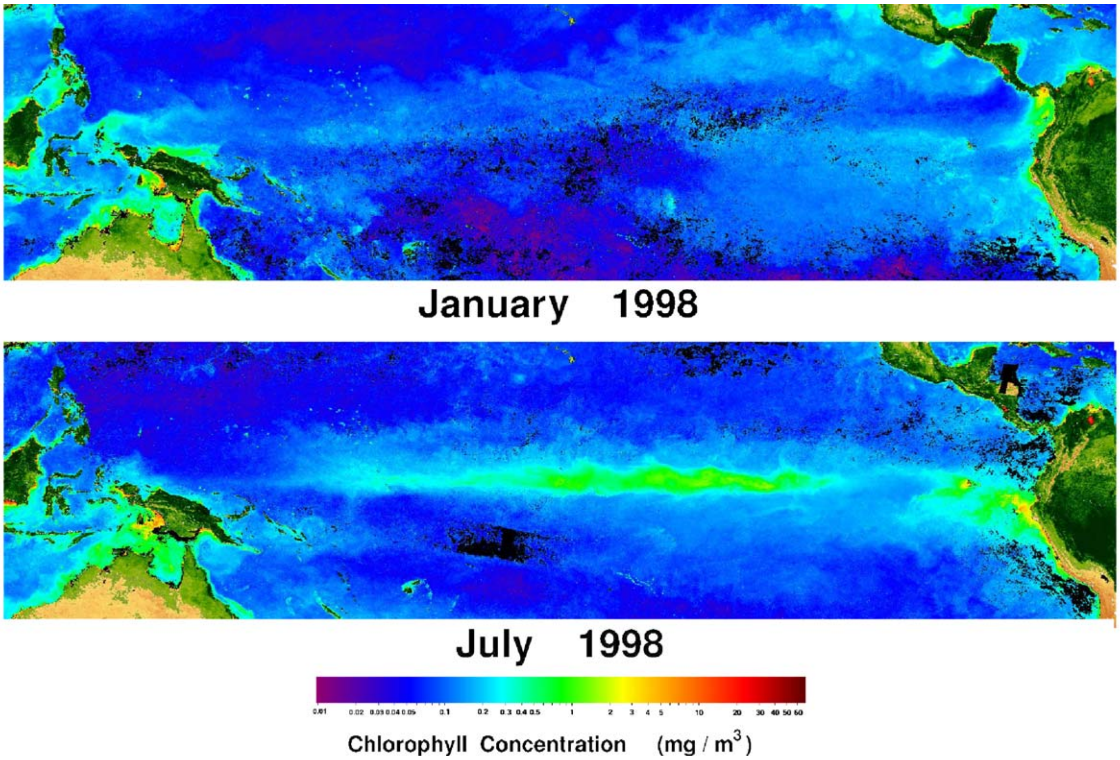

Fig. 11. 1997–1998 El Niño-La Niña. The most noteworthy event to date during the SeaWiFS mission was the 1997–1998 El Niño-La Niña, which was the most intense on record (McPhaden, 1999). The equatorial Pacific ecosystems transitioned from extremely low chlorophyll concentrations over the winter of 1997–1998 to the highest concentrations ever recorded during the summer of 1998 (Chavez et al., 1999; Murtugudde et al., 1999). These extremes are illustrated in the January and July 1998 monthly composites.

and Applications, Inc., and Futuretech Corporation) have provided a talented and dedicated support staff from the beginning of the SPO. The GSFC Public Affairs Office, particularly Wade Sisler, has worked vigilantly with the SPO to quickly get data products to the news media during special geophysical events. Similarly, the GSFC Visualization Laboratory has provided many excellent video sequences for press conferences and special presentations. The CV element has worked closely with a number of international programs, such as the AMT, under LOAs with Plymouth Marine Laboratory in the United Kingdom (Jim Aiken, P.I.), the Joint Research Center in Ispra, Italy (Giuseppe Zibordi, P.I.), and the Laboratoire d'Océanographie de Villefranche in Villefranche-sur-Mer, France (Hervé Claustre, David Antoine, and André Morel, co-investigators). The SPO is indebted to several members of the MODIS oceans team who have made a variety of major contributions to the SPO including Wayne Esaias, Dennis Clark, Bob Evans, Howard Gordon, and Ken Carder. The SPO's collaborations with NIST, mainly Carol Johnson, has been invaluable to the calibration of not only the SeaWiFS sensor, but also in situ data. Watson Gregg deserves special recognition, as the Mission Operations element leader from the beginning of the SPO through data acceptance. Four individuals have served as SPO Managers: Bob Kirk oversaw the early phases of the SPO through the acceptance of the SeaWiFS instrument; Mary Cleave guided the SPO through much of the spacecraft acceptance and launch; Chuck McClain

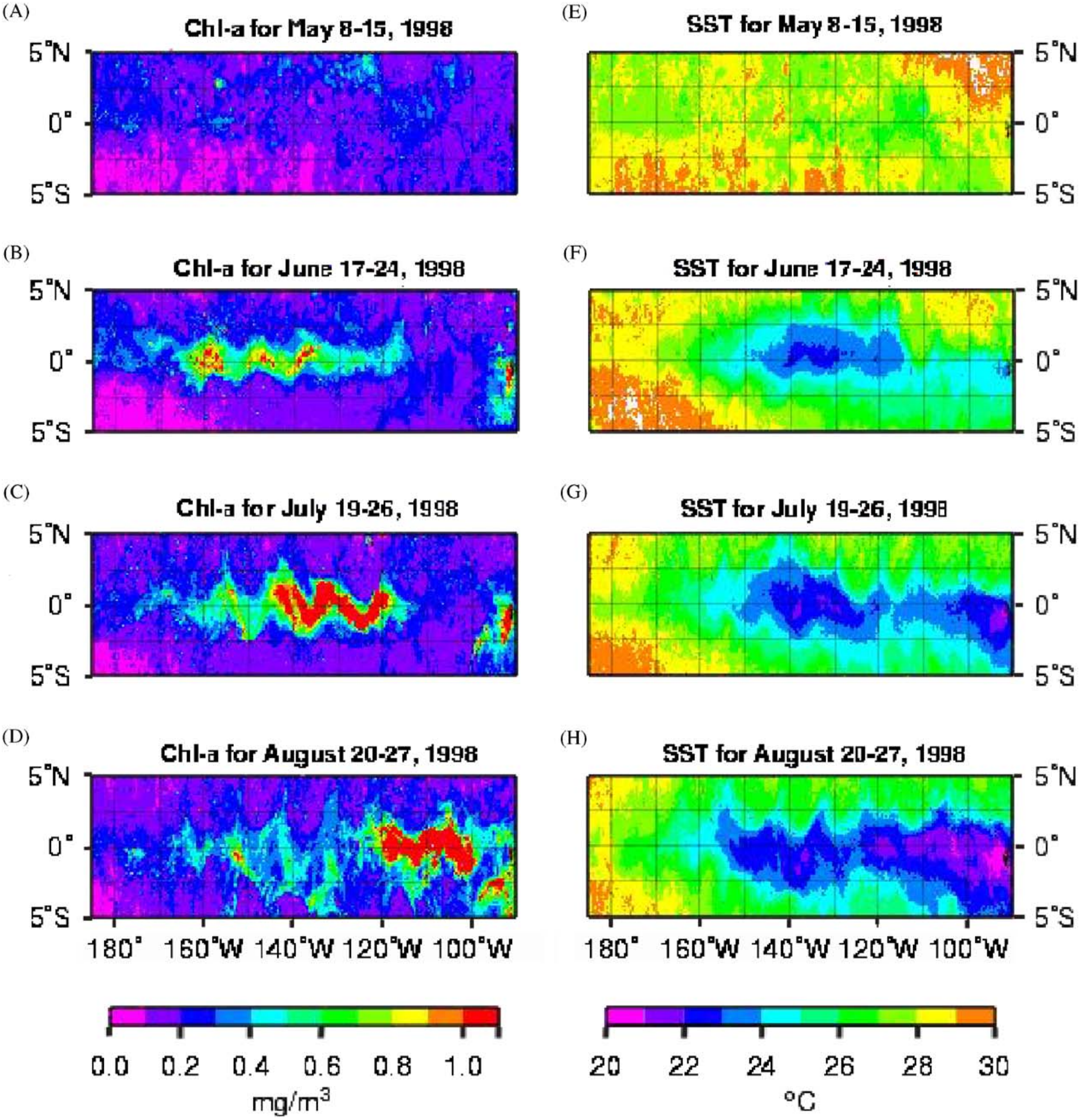

Fig. 12. The 1998 La Niña equatorial Pacific bloom time series. While the July 1998 monthly chlorophyll composite indicates the areal extent of the bloom over a month's time, the bloom was actually moving eastward rapidly and was much smaller in size (Strutton et al., 2001). This figure shows four 8-day composites of SeaWiFS chlorophyll and the corresponding composites of sea surface temperature (SST) illustrating the high coherence between the two fields and the wave structure associated with the bloom.

directed the SPO through data acceptance and the first three reprocessings; and Gene Feldman has guided the SPO during the fourth reprocessing and the negotiations for the extended SeaWiFS mission. Finally, the ocean-color research community has provided unwavering support and assistance

Table 4

Summary of major SeaWiFS program accomplishments
1. First global biosphere data set from a single instrument.
2. Uninterrupted global data reception, product generation, and product archival and release since first day of on-orbit data collection (18 September 1997).
3. First mission to operationally use the moon to track sensor stability on-orbit.
4. Four major reprocessings completed.
5. Data product accuracy goals surpassed.
6. Over 2300 authorized research users.
7. Routine distribution of 9 times the archive product data volume.
8. SeaDAS user sites in nearly 50 countries.
9. Over 70 NASA technical memoranda published and distributed to the user community.
10. Over 400 field experiments supported with coverage predictions and/or real-time data.
11. Over 120 HRPT stations established with data decryption capabilities.
12. Staff participation in over 20 field deployments.
13. Initiation and support of numerous calibration and pigment round-robins, field instrument design studies, and measurement protocol development activities.
14. Over 1250 cruise data sets ingested into SeaBASS.
15. Successful data buy contract with Orbital Sciences Corp. and ORBIMAGE.

to the SPO throughout the SeaWiFS program which has been a great encouragement.

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