

SIMBIOS Program in Support of Ocean Color Missions: 1997-2003

Giulietta Fargion*, Bryan Franz, Ewa Kwiatkowska and Christophe Pietras
Science Applications International Corporation (SAIC), Beltsville, Maryland

Sean Bailey, Joel Gales and Gerhard Meister
FutureTech Corporation, Greenbelt, Maryland

Kirk Knobelspiesse and Jeremy Werdell
Science Systems and Applications Inc., Greenbelt, Maryland

Charles McClain
NASA Goddard Space Flight Center, Greenbelt, Maryland

ABSTRACT

The NASA Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Program had a worldwide, ongoing ocean color data collection program, as well as an operational data processing and analysis capability. SIMBIOS data collection takes place via the SIMBIOS Science Team. In addition, SIMBIOS had a calibration and product validation component (Project Office). The primary purpose of these calibration and product validation activities were to (1) reduce measurement error by identifying and characterizing true error sources, such as real changes in the satellite sensor or problems in the atmospheric correction algorithm, in order to differentiate these errors from natural variability in the marine light field; and (2) evaluate the various bio-optical and atmospheric correction algorithms being used by different ocean color missions. For each sensor, the SIMBIOS Project reviews the sensor design and processing algorithms being used by the particular ocean color project, compares the algorithms with alternate methods when possible, and provides the results to the appropriate project office.

Keywords: SeaWiFS, MODIS, MOS, OCTS, OSMI, POLDER, data merger, SIMBIOS, calibration, validation.

1. INTRODUCTION

The SIMBIOS Program was conceived in 1994 as a result of a NASA management review of the agency's strategy for monitoring the bio-optical properties of the global ocean through space-based ocean color remote sensing. At that time, the NASA ocean color flight manifest included two data buy missions, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Earth Observing System (EOS) Color, and three sensors, two Moderate Resolution Imaging Spectroradiometers (MODIS) and the Multi-angle Imaging Spectro-Radiometer (MISR), scheduled for flight on the EOS-Terra and EOS-Aqua satellites. The review led to a decision that the international assemblage of ocean color satellite systems provided ample redundancy to assure continuous global coverage, with no need for the EOS Color mission. At the same time, it was noted that non-trivial technical difficulties attended the challenge (and opportunity) of combining ocean color data from this array of independent satellite systems to form consistent and accurate global bio-optical time series products. Thus, it was announced at the October 1994 EOS Interdisciplinary Working Group meeting that some of the resources budgeted for EOS Color should be redirected into an intercalibration and validation program¹.

NASA Goddard Space Flight Center (GSFC) was directed to develop an intercalibration and validation program plan for submission to NASA Headquarters (HQ) by May 1995. This plan envisioned a Science Team funded by a NASA Research Announcement (NRA) (released in July 1996) and the SIMBIOS Project Office that was established at GSFC in January 1997. The initial SIMBIOS Program was scoped for five years (1997-2001) and included separate support for a science team and the Project Office. Dr. Mueller (San Diego State University) acted as an interim project manager at GSFC under a one-year assignment to assist in getting the project office organized and the science team contracts executed. During the second year of the SIMBIOS Project, Dr. McClain assumed project management for SeaWiFS and SIMBIOS, as both Dr. Cleave and Dr. Mueller stepped down in their roles as project managers of these two projects, respectively. In Fall 1998, Dr. Fargion was hired as Deputy Project Manager to assist Dr. McClain.

*gfargion@simbios.gsfc.nasa.gov; phone 1 301 286-0744; fax 1 301 286-0268; simbios.gsfc.nasa.gov

In September 2000, Dr. McClain assumed new responsibilities in assisting HQ to develop a long-term program for global carbon cycle research. As a result, SeaWiFS and SIMBIOS Project Office were reorganized somewhat to allow Dr. McClain to focus on the carbon initiative. Dr. Feldman assumed management responsibilities for SeaWiFS and Dr. Fargion for SIMBIOS, respectively. Due to the success of the SIMBIOS Program combined with a strong collaboration with the US and international ocean communities, HQ release a second NRA (1999) and granted an extension of three years to the project. However, last year NASA HQ decided to discontinue the program in its present form. The rationale centered on three considerations. The first was a desire by HQ to integrate the various ocean color calibration and validation activities of the SIMBIOS, SeaWiFS, and the MODIS programs under a common ocean color team which would also include investigators supported under the NASA Ocean Biogeochemistry program. While the three ocean color projects have separate management and funding structures, they have been coordinated and mutually supportive with little redundancy. The second consideration stems from initial problems with MODIS ocean data quality and accessibility which has made it imperative for NASA to focus its available resources on MODIS ocean calibration and validation. The third consideration is the National Polar Orbiting Environmental Satellite System (NPOESS) Preparatory Project (NPP), which is scheduled to launch in 2006. The SIMBIOS Project Office, co-located with the SeaWiFS Project Office, provides support and coordination for the SIMBIOS Program, such as administration, project documentation, and interagency and international coordination. It also incorporates aspects of post launch calibration & characterization, *in situ* data collection, protocol developments, round robins, algorithm development and evaluation, product merging, and data processing (Figure 1). All components illustrated in Figure 1 are tightly connected (and in some cases overlap) and were thoroughly developed and integrated by the Project during the operational years (1997-2003).

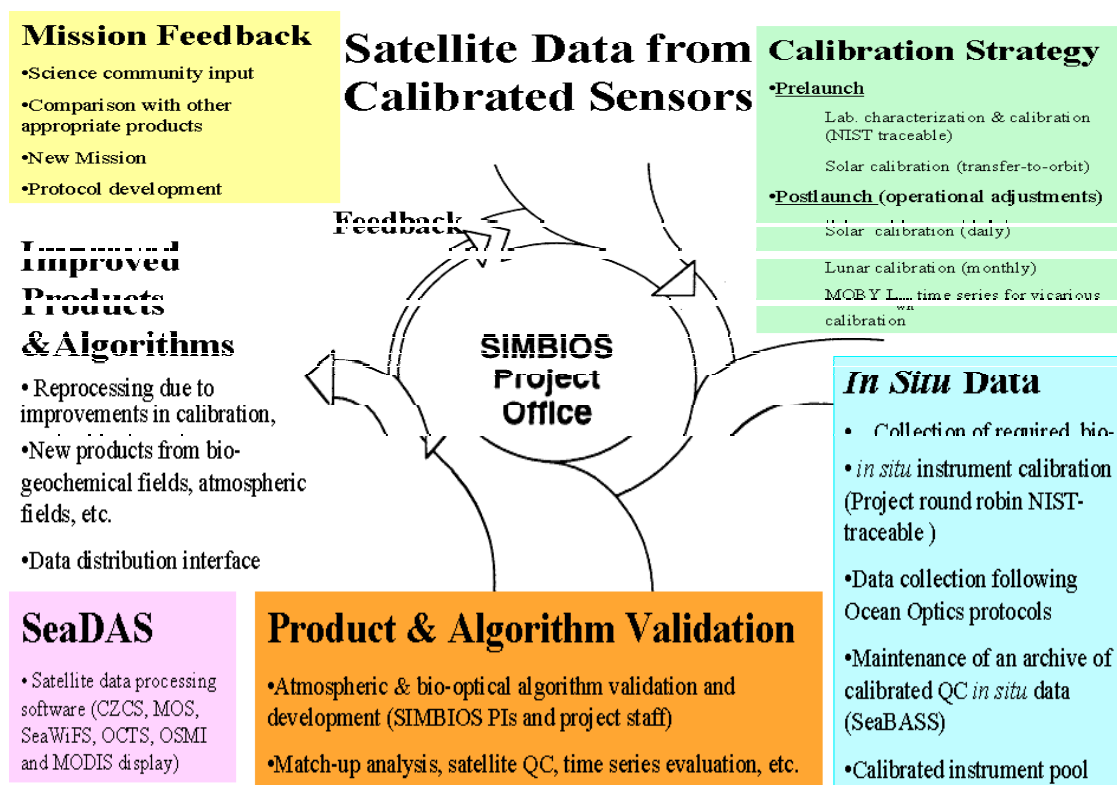


Figure 1. SIMBIOS Project activity areas

The specific proposed objectives of the SIMBIOS Program were: (1) to quantify the relative accuracy of measurements from the ocean color products from each mission, (2) to work with each project to improve the level of confidence and compatibility among these products, and (3) to develop methodologies for generating merged level-3 products. These objectives have been operational and research requirements. In particular, the intercomparison

component performs many functions similar to those being performed by each individual mission (calibration, validation, quality control, algorithm development and data processing) but does so by integrating information from each project, augmenting activities where required, providing feedback to each project and the ocean color community, and coordinating with the international community. SIMBIOS has worked with several missions, such as SeaWiFS, Ocean Color & Temperature Scanner (OCTS), Polarization and Directionality of the Earth's Reflectances (POLDER), Modular Optoelectronic Scanner (MOS), Ocean Scanning Multispectral Imager (OSMI), MODIS (Terra and Aqua), Medium Resolution Imaging Spectrometer (MERIS) and Global Imager (GLI). The Project staff ensured the development of internally consistent research products and time series from multiple satellite ocean color data sources; developed methodologies for cross-calibration of satellite ocean color sensors; developed methodologies for merging data from multiple ocean color missions; promoted cooperation between ocean color projects, and served as a prototype for future Earth observation programs. In order to better communicate with the community, the project held annual open science team meetings and workshops, participated as a member in several mission teams, documented all activities in NASA technical manuals (TM) and hosted a web site organized to serve as the main information resource of Project activities, the Project Office, and the Science Team. The Project Office, in an effort to educate and promote the concept of an organized program of sensor cross-calibration and validation, had send representatives to several international conferences. Many of the original objectives and activities of SIMBIOS are discussed in more detail in the SIMBIOS Project Annual Report ²⁻⁶, Ocean Optics Protocols ⁷⁻⁸ and round robin activities ⁹⁻¹².

2. SIMBIOS SCIENCE TEAM

The SIMBIOS Science Team was selected through NRA's 1996 and 1999. NASA HQ manages the process of team selection, but the GSFC NASA Procurement Office handles the team contracts, work statements and, if necessary, budget negotiations. The Project funds numerous US investigators and collaborates with several international investigators, space agencies [e.g., National Space Development Agency of Japan (NASDA), European Space Agency (ESA), Korea Aerospace Research Institute (KARI)] and international organizations [e.g., International Ocean Colour Coordinating Group (IOCCG), Joint Research Center (JRC)]. US investigators under contract provide *in situ* atmospheric and bio-optical data sets, and develop algorithms and methodologies for data merger schemes. NASA Procurement requires formal evaluations for all contracts at the end of each contract year. These evaluations go into a database and are shared with the PI's institution or upper management. The locations of specific SIMBIOS team investigations are shown in Figures 2 and 3.

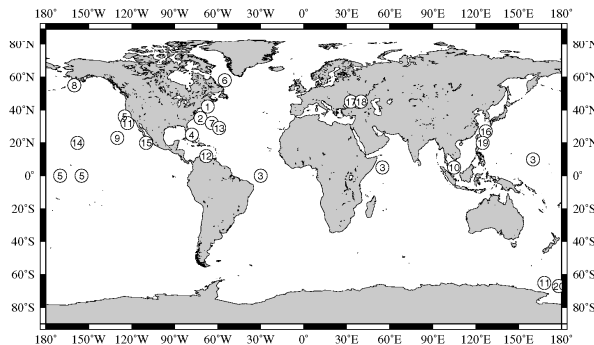


Figure 2. Global distribution of the NRA-96 selected SIMBIOS studies. United States (field): (1) Balch; (2) Brown/Brock; (3) Capone/Carpenter/Subramaniam and Miller; (4) Carder and Green; (5) Chavez; (6) Cota; (7) Dickey; (8) Eslinger; (9) Frouin; (10) Miller; (11) Mitchell and Green; (12) Müller-Karger; (13) Siegel; (14) Porter (15) Zaneveld and Mueller. United States (theoretical): Flatau; Siegel and Stannes/Chen. International: He; Korotaev; Kopelevich; and Li.

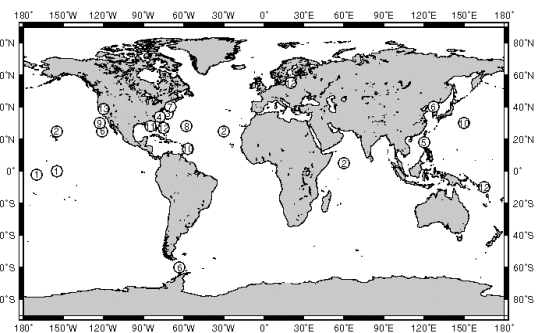


Figure 3. Global distribution of the NRA-99 selected SIMBIOS studies. United States (field): (1) Chavez; (2) Frouin; (3) Gao; (4) Harding; (5) Miller; (6) Mitchell; (7) Morrison; (8) Nelson; (9) Siegel; (10) Spinhirne; (11) Stumpf; (12) Subramaniam; (13) Zalewski. United States (theoretical): Gregg; Hooker; Maritorena; Mueller; Trees and Wang. International: Bohm; Zibordi; Fougnie; Deschamps; Antoine; Kopelevich; Ishizaka; Fukushima; Chen; Li and Lynch.

The international ocean color community's response to NRA-99 was overwhelming: a total of 75 PI's proposed collaboration with the Project. The twelve international proposals covered topics ranging from protocols, calibration-

validation activities, atmospheric-biological algorithms, and data merging. The SIMBIOS Science Team meetings were held in August 1997 at Solomons Island (Maryland), in September 1998 at La Jolla (California), in September 1999 at Annapolis (Maryland), in January 2001 at GSFC (Maryland), and in January 2002 at Baltimore (Maryland). SIMBIOS Science meetings had a large US and international attendance, including participation of space agencies and international organizations. During each year the Project at GSFC has fostered several US and international visiting scientists, staying from 2 weeks to one year (e.g., Dr. Antoine, Dr. Deschamps, Dr. Frouin, Dr. Fukushima, Dr. Hagolle, Dr. Kopelevich, Dr. Miller, Dr. Nicolas, Dr. Souaidia, Dr. Subramaniam, Dr. Tanaka, Dr. Yamamoto and Dr. Zibordi).

3. OCEAN COLOR SATELLITE DATA PROCESSING

Over the past years, the SIMBIOS Project has been engaged in the characterization, validation, intercomparison, and cross-calibration of a host of space-borne ocean color sensors. This work has included the characterization and calibration of OCTS and POLDER¹³, the cross-calibration and long-term intercomparison of MOS and SeaWiFS¹⁴⁻¹⁵, the cross-calibration of OSMI to SeaWiFS¹⁶, and the intercomparison of MODIS/Terra⁶ and MODIS/Aqua with SeaWiFS, as well as independent validation of MODIS (Terra & Aqua), SeaWiFS, OCTS, and POLDER using coincident *in situ* measurement archived in SeaWiFS Bio-optical Archive and Storage System (SeaBASS). To facilitate the processing and intercomparison of ocean color products from multiple instruments, the SIMBIOS Project developed atmospheric correction code based on the SeaWiFS algorithm of Gordon and Wang¹⁷. The approach was to identify those few parts of the algorithm which were sensor or band-pass specific, and develop a software package which could process data from multiple ocean color sensors with minimal changes in the algorithms. The sensitivity of the atmospheric correction algorithm to differences in spectral bands was carefully assessed by Wang¹⁸, wherein he showed by simulation that these differences can be accurately accounted for through exact calculation of the Rayleigh reflectances and minor modifications to the diffuse transmittance calculation. The multi-sensor level-1 to level-2 code (MSL12) has been used to process data from MOS, OCTS, POLDER, OSMI, and SeaWiFS, with support for MODIS currently underway. Due to its enhanced flexibility and maintainability, the software was adopted by the SeaWiFS Project for all standard production, calibration, and validation activities and is widely distributed and utilized by the international ocean color community through the SeaWiFS Data Analysis System (SeaDAS). Using MSL12, the SIMBIOS Project performed an independent vicarious calibration of the OCTS sensor, then reprocessed the entire global OCTS mission archive. This data was distributed through the Goddard DAAC, with processing and display support distributed through SeaDAS, thereby providing the ocean color community with a nearly complete, highly compatible ocean color time-series from September 1996 to the present day, including the first complete record of an El Niño/La Niña event. The SIMBIOS Project also developed and evaluated methods for cross-calibration of ocean color sensors, beginning with the MOS and SeaWiFS instruments. The MOS is a German ocean color sensor flying on the Indian Space Agency IRS-P3 satellite. Because the sensor has a small swath width of 192 km and only four ground stations capable of receiving the real time-only transmissions, there is limited opportunity for ground truth. In addition, the sensor is a push-broom CCD array with 384 independent detectors in each band, so calibration requires both a cross-scan, detector-relative calibration and an absolute calibration. As a prototype for future missions, the SIMBIOS Project developed a technique to vicariously calibrate MOS using SeaWiFS¹⁵. The method is analogous to that used by the SeaWiFS Project for vicarious calibration to MOBY, except that for MOS the Project used SeaWiFS observations rather than MOBY measurements as truth. A major advantage of this technique is that the Project was able to obtain a large number of matchups for each detector of each band, and thus derive both the absolute and detector-relative calibrations simultaneously. This vicarious cross-calibration, coupled with the instrument calibration performed by the MOS Project, has enabled the retrieval of oceanic optical properties which maintain good agreement with SeaWiFS, even after three years¹⁴. The SIMBIOS Project performed a similar cross-calibration between SeaWiFS and OSMI¹⁶. OSMI is a whisk-broom scanning CCD array with 96 detectors per band distributed along track. The detectors are divided into two independently amplified fields of 48-detectors each. Prior to cross-calibration, the calibrated level-1B radiances exhibited significant interdetector striping, banding between the detector fields, and absolute radiances that were below the predicted Rayleigh radiance in most bands. As such, it was not even possible to compute oceanic optical properties, as any atmospheric correction would fail. In this case, it was necessary to develop a calibration for the NIR channels as well as the visible bands. The NIR calibration was performed using the SeaWiFS retrieved aerosol optical thickness as truth, using a technique originally developed to calibrate SeaWiFS to *in situ* aerosol optical thickness measurements¹⁹. Once the NIR calibration was established, the calibration of the visible bands proceeded in a manner analogous to the MOS-to-SeaWiFS cross-calibration, with independent gains derived for each detector of each band. After this cross-calibration it was possible, for the first time, to process an OSMI scene and retrieve meaningful oceanic optical properties. The final year of the SIMBIOS Project was largely dedicated to MODIS analyses. An extensive evaluation of the temporal trends in several

standard ocean color products derived from SeaWiFS and MODIS/Terra was performed to determine the long-term relative stability between the two sensors and to develop an understanding of their similarities and differences. This time-series analysis investigated variations in the mean value of water-leaving radiance and chlorophyll products over the period from March 2000 through December 2002, for both global and regional geographic areas, between MODIS Collection #4 and SeaWiFS Reprocessing #4. The analysis was able to demonstrate the remarkable temporal stability of SeaWiFS, and assess the long-term stability of MODIS/Terra (see http://simbios.gsfc.nasa.gov/simbios_modis.html). This work has provided critical insight into the issues and limitations associated with the establishment of a long-term, multi-mission, climate data record for ocean color.

Data Merger

The objective of ocean color data merger is to create a consistent series of systematic ocean color measurements from multi-instrument, multi-platform and multi-year observations based on accurate and uniform calibration and validation over the lifetime of the measurement. The most obvious benefit of data merger is improvement in spatial and temporal ocean color coverage. Data merger is the ultimate tool for the creation of ocean color climate data records. The major data merger effort undertaken by the SIMBIOS Project focused on integrating daily MODIS/Terra and SeaWiFS chlorophyll data sets. MODIS and SeaWiFS data were used to study methodologies to create a consistent series of long-term observations from sensors of different design, characterization, processing algorithms, and calibrations. Analyses of MODIS/Terra²⁰ daily oceans data in comparison with SeaWiFS were performed to facilitate the merger efforts (<http://simbios.gsfc.nasa.gov/~ewa/SeaMODIS/seamodis-match.html>). The analyses focused on assessing temporal trends in data discrepancies between MODIS and SeaWiFS and artifacts present in MODIS data caused by the difficulties in accurately characterizing this complex sensor for features such as polarization sensitivity. A time series of daily water-leaving radiance and chlorophyll products, evenly spread over the three years of joint MODIS/Terra and SeaWiFS coverage, was used to study MODIS trends in departure from SeaWiFS data and MODIS scan angle and latitudinal dependencies. Corresponding investigations were performed on a three-month time series of provisional MODIS/Aqua data and concurrent SeaWiFS coverage (<http://simbios.gsfc.nasa.gov/~ewa/SeaMODISAqua/seamodis-aqua.html>). The analyses provided vital information on MODIS data dependencies in relation to SeaWiFS ocean color records for the data merger activity. The information derived from MODIS/Terra and SeaWiFS comparisons was used to derive an ocean color sensor cross-calibration strategy where sensor artifacts, temporal, and spatial variabilities are not easily quantifiable and many dependencies are involved. Machine learning techniques were developed to cross-calibrate MODIS/Terra and SeaWiFS and produce a consistent and calibrated global ocean color baseline data set. The cross-calibration enabled to produce combined MODIS and SeaWiFS daily global chlorophyll coverages which were free from temporal trends, and MODIS scan angle and latitudinal dependencies²¹. An example of the cross-calibration result is shown in Figure 4. Statistical objective analysis was investigated to spatially and temporally interpolate MODIS/Terra (cross-calibrated with SeaWiFS) and SeaWiFS data onto daily global ocean color maps²²⁻²³. The objective of the interpolation was to merge ocean color data sets using individual sensor chlorophyll accuracies and produce error bars for each data point. An addition to conventional statistical objective analysis was proposed to perform both space and time interpolation of ocean color data. Furthermore, the ensemble spatial and temporal correlation structure of the chlorophyll field was made dependent on the ocean spatial variability defined by local dynamical processes. An effort was made to merge ocean color data of different spatial resolutions to support data merger applications focused on local area coverage, such as on coastal zones. A wavelet transform multi-resolution analysis was applied to overlapping MOS and SeaWiFS scenes, where MOS data were at 0.5km resolution and SeaWiFS at 1.1km resolution^{22 & 24}. The approach enabled enhancement of oceanic features in lower resolution imagery using higher resolution data.

4. VALIDATION OF BIO-OPTICAL PROPERTIES

A standard set of measurement protocols is indispensable in developing consistency across the variety of international satellite ocean color missions either recently launched or scheduled for launch in the next few years. The SeaWiFS and SIMBIOS Projects allocated resources to describe and develop protocols or scientific approaches in accordance with the goals of the Projects⁷⁻⁸. These efforts, described in NASA TMs, are intended to provide standards, which if followed carefully and documented appropriately, will ensure that any particular set of optical measurements will be acceptable for ocean color sensor validation and algorithm development⁷⁻⁸. The protocols are guidelines and may be somewhat conservative. Continued development and refinement of these protocols help ensure coordination, collaboration, and communication between those involved. Furthermore, calibration round-robin intercomparison experiments are conducted by the Project. The SIMBIOS and SeaWiFS Projects maintained a local repository of *in situ*

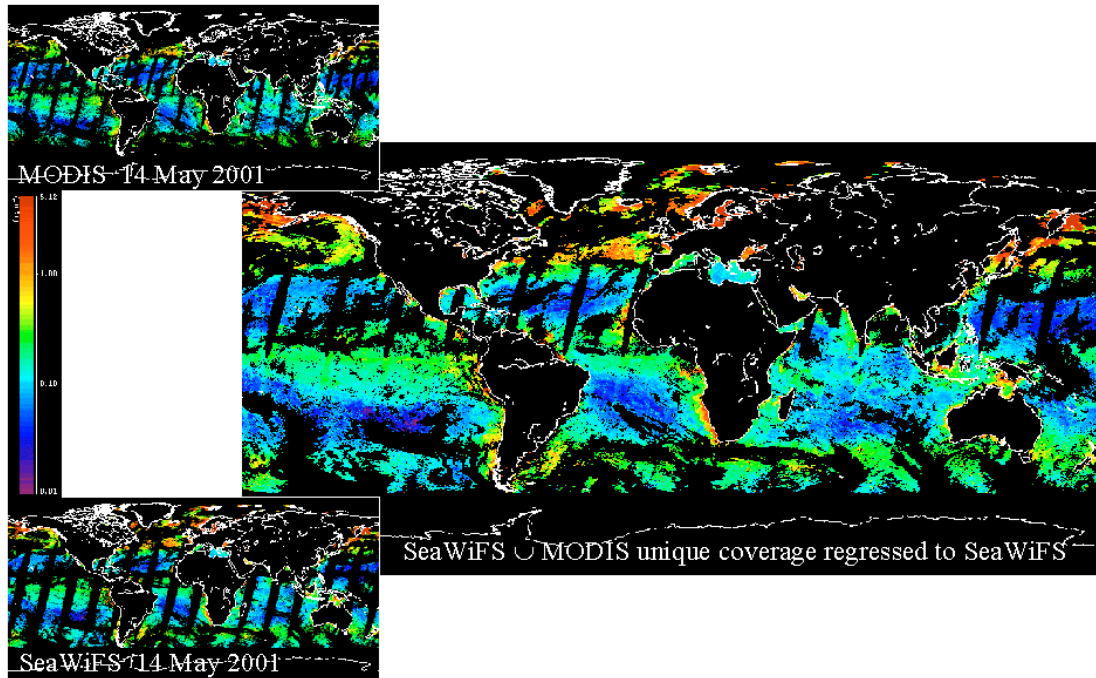


Figure 4. Result of machine learning cross-calibration of MODIS and SeaWiFS data. A merged, consistent daily chlorophyll map was produced using original SeaWiFS chlorophyll and MODIS data regressed to SeaWiFS baseline chlorophyll representation.

bio-optical data, known as the SeaBASS, to support and sustain their regular scientific analyses²⁵⁻²⁶. This system was originally populated with radiometric and phytoplankton pigment data used in the SeaWiFS Project's satellite validation and algorithm development activities. To facilitate the assembly of a global data set, SeaBASS was broadened to include oceanographic and atmospheric data sets collected by the SIMBIOS Project, which aided considerably in minimizing spatial and temporal biases in the data while maximizing acquisition rates⁶. To develop consistency across multiple data contributors and institutions, the SIMBIOS Project also defined and documented a series of *in situ* sampling strategies and data requirements that ensure that any particular set of measurements are appropriate for algorithm development and ocean color sensor validation¹⁻⁷. The SeaBASS bio-optical data set includes measurements of apparent and inherent optical properties, phytoplankton pigment concentrations, and other related oceanographic and atmospheric data, such as water temperature, salinity, and aerosol optical thickness (AOT). Data were collected using a number of instrument packages from a variety of manufacturers, such as profilers and handheld instruments, on a variety of platforms, including ships and moorings. As of April 2003, SeaBASS included data collected by research groups at 44 institutions in 14 countries, encompassing over 1,150 individual field campaigns, including major international field experiments, such as the Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia) and the Indian Ocean Experiment (INDOEX) (Figure 5). The full data set includes over 300,000 phytoplankton pigment concentrations, 13,500 continuous depth profiles, 15,000 spectrophotometric scans, and 15,000 discrete measurements of AOT. Participants of the SIMBIOS Program contributed just over 87% of these data. The SIMBIOS Project Office made use of a rigorous series of submission protocols and quality control metrics that range from file format verification to inspection of the geophysical data values^{8 & 26}. This ensures that observations fall within expected ranges and do not exhibit any obvious characteristics of measurement problems. A consistent methodology for validating satellite data retrievals was developed and applied to OCTS, MOS, POLDER, SeaWiFS and MODIS provides a means of objectively analyzing validation results across missions by minimizing the effect of processing differences on the overall results. Briefly, the validation analysis requires coincident measured *in situ* and satellite observations, quality controlled data sets (both satellite and *in situ*), derived from a well defined, objective set of exclusion criteria²⁷. An example of these validation results for SeaWiFS and MODIS (Terra) are presented in Figure 6. The SeaBASS World Wide Web site, located at: <http://seabass.gsfc.nasa.gov>, provides a complete description of the system architecture, comprehensive documentation on policies and protocols, and direct access to the bio-optical data set and validation results. Briefly, the architecture consists of geophysical data and metadata recorded in digital ASCII text files, which reside on a dedicated server at NASA GSFC, and a relational database management system (RDBMS) used to catalog and distribute the data and files.

Through the use of online search engines that interface with the RDBMS, the full bio-optical data set is queryable and available to authorized users via the Web. To protect the publication rights of contributors, access to data collected more recently than January 1, 2000 is limited to SIMBIOS Science Team members, NASA-funded researchers, and regular voluntary contributors, as defined by the SeaBASS access policy²⁸. The remainder of the data is fully available to the public and, additionally, has been released to the National Oceanic and Atmospheric Administration's (NOAA) National Oceanographic Data Center (NODC) for inclusion in their archive. As of April 2003, 41 research groups outside of the SIMBIOS and SeaWiFS Project Offices have been granted unrestricted access to SeaBASS. In 2002, these groups queried SeaBASS over 950 times and downloaded more than 60,000 data files from the bio-optical data set. During the same period, 146 research groups searched the public set 600 times and downloaded over 37,000 files.

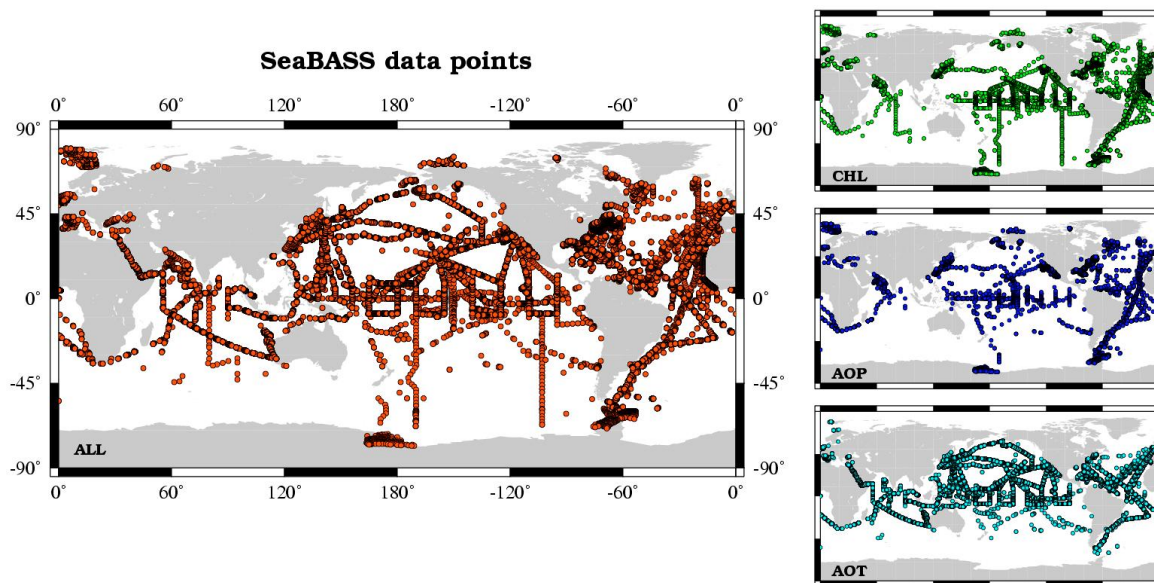


Figure 5. The global distribution of data included in the full SeaBASS bio-optical data set, as of April 2003. Clockwise from left: all archived data, chlorophyll a concentrations only (CHL), apparent optical properties only (AOP), and aerosol optical thickness only (AOT).

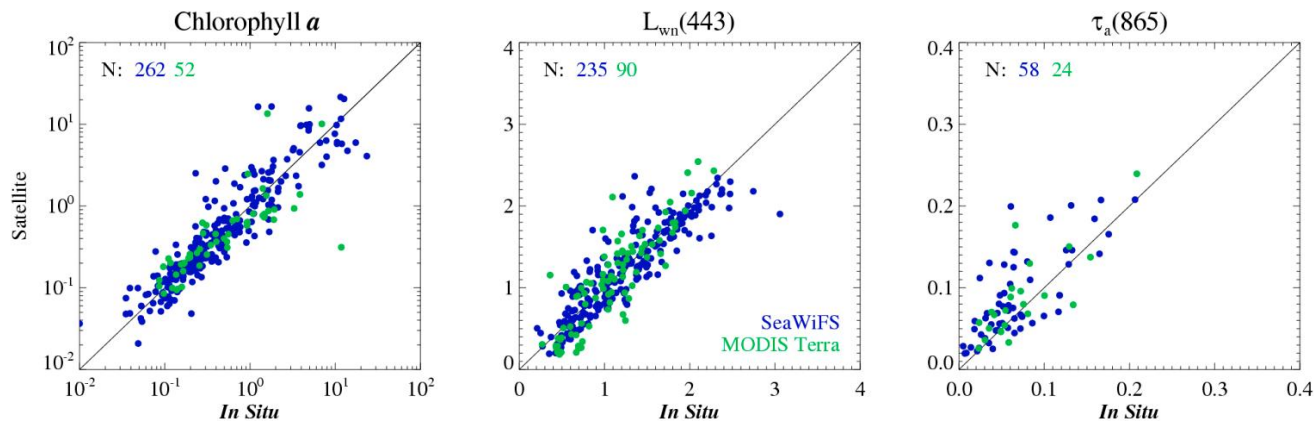


Figure 6. Scatter plots of coincident *in situ* and SeaWiFS (blue) and MODIS Terra (green) observations for chlorophyll *a*, water-leaving radiance (L_{wn}) at 443 nm, and aerosol optical thickness (τ_a) at 865 nm. The chlorophyll *a* data were transformed to account for their log-normal distribution. A one-to-one line has been included for clarity.

5. SUPPORT SERVICES

In an effort to improve the quality and quantity of calibration and validation data sets, the SIMBIOS Project offered several support services to field investigators and larger ocean color community. As of April 2003, 352 cruises have been

supported by the Project. These services include: scheduling of on-board Local Area Coverage (LAC) recording for SeaWiFS; over flight predictions for operational sensors; near real time SeaWiFS imagery for cruise locations; satellite data distribution and software support; optical instrumentation from a pool of investigator and project owned instruments; and round robin activities. Detailed information on the services is available on the SIMBIOS web site (<http://simbios.gsfc.nasa.gov/>).

Scheduling SeaWiFS On-board LAC Recording

Since much of the world's oceans are not covered by a SeaWiFS High Resolution Picture Transmission (HRPT) station, high-resolution data may have been recorded onboard the SeaWiFS sensor. As a service to the science community, the SIMBIOS Project, in conjunction with the SeaWiFS Project, scheduled SeaWiFS onboard LAC for cruises that occurred outside HRPT coverage. SeaWiFS has the ability to record a maximum of 10 minutes of high-resolution data per downlink. Typically, a 30-second interval was allotted for each LAC target, which corresponded to 180 scan lines or approximately 200 km along track at nadir.

Overflight Predictions for Operational Sensors

For calibration and validation purposes, *in situ* measurements should be made as close to the sensor over-flight time as possible. To aid investigators in determining when sampling should occur, the SIMBIOS Project offered over-flight predictions for all operational ocean color remote sensors. The sensors supported were SeaWiFS, MOS, Ocean Color Imager (OCI), OSMI, MERIS and MODIS (Terra & Aqua).

Near Real Time SeaWiFS Imagery

In addition to providing predictions for satellite over-flight times, the SIMBIOS Project offered near real time imagery of the operational SeaWiFS products to cruises at sea in JPEG format. These images provided field investigators with additional information, which assisted in maximizing *in situ* sampling of transient oceanographic features. The default specifications for the images provided included: available LAC, HRPT, and Global Area Coverage (GAC); chlorophyll *a* and pseudo-true color images of a 2⁰ box about a designated location or the entire designated region; and image width of 600 pixels; and a minimum percent yield (5%) of valid chlorophyll pixel. Images were customized to best accommodate individual investigator needs.

Satellite Data Distribution

The OCTS is an optical radiometer which flew on the Japanese Advanced Earth Observing Satellite (ADEOS) from August 1996 to June 1997, collecting 10-months of global ocean color data. During the ADEOS mission lifetime, approximately 450 GB of real-time, 700m-resolution OCTS data were collected by the SeaWiFS project through NOAA ground stations at Wallops, Virginia and Fairbanks, Alaska. The archive consists of 337 scenes of the U. S. East Coast and 1,311 scenes over Alaska. These data were processed from raw telemetry through level-2 ocean color products using software developed by SIMBIOS and products distributed through a browse utility linked to the SIMBIOS Project's web site. Furthermore, the entire OCTS GAC data was reprocessed by the Project in 2001. This was a very productive collaboration with NASDA and Japanese scientists. OCTS-GAC data is available through the GSFC DAAC, the SIMBIOS Project and NASDA. Descriptions of the data processing stream, OCTS-specific modification to the algorithms, and statistical comparisons between OCTS & SeaWiFS can be found at: http://seawifs.gsfc.nasa.gov/SEAWIFS/RECAL/OCTS_Repro1/. Since February 1999, the project has been operating a receiving station at NASA's Wallops Flight Facility (WFF) to acquire data from MOS onboard the Indian IRS-P3 spacecraft. When a pass is acquired at Wallops, the raw files are transferred to the SIMBIOS project at NASA's GSFC via an automated FTP process. The raw files are then converted to level-0 format through a software package provided by the Indian Space Research Organization (ISRO). The resulting level-0 files are made available to the German Remote Sensing Data Centre (DLR-DFD) for archive and distribution. In addition, the SIMBIOS Project processes the data through level-1B using standard software provided by the German Institute for Space Sensor Technology (DLR-ISST)²⁹. All MOS data (1999-2003) processed by the SIMBIOS project is made available through the MOS browse system on the SIMBIOS web page. In coordination with MODIS-Terra Collection 4 reprocessing, the Project initiated an operational process to collect and merge MODIS daily global chlorophyll products with SeaWiFS daily products. The merging scheme is a simple weighted averaging using standard SeaWiFS time-binning software. Presently a complete set of daily, weekly, and monthly merged chlorophyll products, including various perturbations such as MODIS-Terra with MODIS-

Aqua, MODIS-Terra with SeaWiFS, MODIS-Aqua with SeaWiFS, and MODIS-Terra/MODIS-Aqua/SeaWiFS are made available at the SIMBIOS web page (<http://seawifs.gsfc.nasa.gov/cgi/level3.pl?DAY=05Mar2000&PER=&TYP=tmsea>). The merging process is fully automated and operational, with new products generated as soon as the MODIS data became available. The merged products can be displayed and manipulated with standard SeaWiFS software tools such as SeaDAS.

Diagnostic Data Set

During the first three SIMBIOS Science team meetings, it was recommended that a “diagnostic data” set be created for each ocean color sensor to aid in comparing data products and to allow rapid reprocessing of selected areas for calibration and algorithm evaluation. As envisioned, the diagnostic data set would be generated routinely at the time that data are being processed, and would contain all relevant information needed to process data from level 1 through level 2 for a few selected sites. An area surrounding each site would be defined, and each time that a site would be contained in a product being created, all relevant information used in the processing (e.g., calibration factors, sun and sensor viewing angles, meteorological input) would be saved to a separate file along with the derived geophysical variables. Regions were defined and agreed upon by the international community at the fourth science team meeting. Participants included SeaWiFS and MODIS (Terra & Aqua), as well as MERIS and GLI. Since 2001 the Project has been collecting and distributing the MODIS and SeaWiFS diagnostic data sets and developing procedures for comparative analysis (http://seawifs.gsfc.nasa.gov/cgi/seawifs_region_extracts.pl?TYP=ocean). Significant effort was made to coordinate the multiple MODIS granules associated with each region, and to compile the related MODIS products into a single daily file per region, thus making the data more accessible to the ocean color community.

SEADAS Software

The SeaDAS is a comprehensive software package for processing, displaying and analyzing all SeaWiFS data products (<http://seadas.gsfc.nasa.gov>). It was designed to serve a wide range of users, including individual scientists, SeaWiFS ground stations, and operational or commercial users. It was designed to accurately replicate the operational data products, e.g., geophysical fields and data formats, by using their default input values, and also to allow processing flexibility in the algorithms applied, the map projections used, and other aspects of processing and analyses that allow users to customize their data products. The SeaDAS group is co-located with the SeaWiFS and SIMBIOS Projects. SeaDAS was augmented by the SIMBIOS Project to include OCTS, MOS, OSMI, and soon, MODIS. The current SeaDAS user community includes approximately 500 research sites in 45 countries.

Instrument Pool

The Project maintained and deployed over the years a pool of sun photometers and above water radiometers intended to complement in-water optical measurements and the land-based Aerosol Robotic Network (AERONET) sun photometer network. The overall goal was to study aerosol optical properties and validate satellite retrievals of aerosol optical properties. The pool of sun photometers was composed of three types of instruments (<http://simbios.gsfc.nasa.gov/Sunphotometers/>). The first type was a sun/sky photometer that measured the solar irradiance and the sky radiance. The second type was the shadow-band radiometer that measured the diffuse and total sky radiance. The third type was the Micropulse Lidar (MPL), which measured the vertical and horizontal distribution of aerosol backscatter, extinction and optical depth. The instruments were deployed by SIMBIOS or NASA principal investigators on cruises and collected data was archived in SeaBASS. This instrument pool included fourteen Microtops II sun photometers³¹, one SIMBAD and two SIMBADA above water radiometers/sun photometers³², 2 PREDE sun photometers and 1 micro-pulse Lidar. The description, characteristics and advantages of each instrument have been reviewed in project protocols and project annual reports²⁻⁶. In addition to the instrument pool, the Project augmented the existing AERONET, which is dedicated to monitoring aerosol optical thickness (AOT) around the globe by supplying additional CIMELS. Most of the sun photometers used within the AERONET³³ project are in continental zones, and SIMBIOS enhanced this network with island and coastal stations. SIMBIOS CIMEL sites included Lanai Hawaii (with backup in Honolulu, USA), Ascension Island, Bahrain (Turkey), Papeete (Tahiti), Wallops Island (USA), Anmyon Island and Chinae (South Korea), Erdemli (Turkey), Horta (The Azores), Puerto Madryn (Argentina), Dahkla (Morocco) and Rottneest Island (Australia). This deployment activity ended in 2001 and all instrument are now managed by the AERONET group. SIMBIOS had taken a number of steps to ensure the consistency and quality of this atmospheric data set. Calibration was performed about every three months⁶. Details on the operation, calibration and theoretical principles

of sun photometry are posted at <http://simbios.gsfc.nasa.gov/Sunphotometers/principle.html>. To aid the organization and dissemination of collected data, the sun photometer instrument pool Web site posts information about the deployment and data processing status of each instrument, along with calibration coefficient histories. Several steps were taken to ensure data quality consistency from several instrument designs. The ACE-Asia cruise, on the R/V Ron Brown, was an ideal platform to validate SIMBIOS sun photometers. The R/V Ron Brown, which departed from Hawaii on March 15, 2001 and arrived in Yokosuka, Japan on April 19, 2001, encountered a variety of aerosol types, from maritime low optical thickness conditions to extremely high optical thickness due to Asian dust. Visual inspections of data time series suggest that despite differences in instrument design, calibration and deployment, AOT and Ångström exponent typically agree within uncertainties. Data from instruments whose bands (1) have similar (within 10nm) center wavelengths, and (2) have calculated uncertainty values were analyzed to find measurements taken within fifteen minutes of each other. These temporally similar measurements were plotted to assess trends or biases between the data. Nearly all AOT and Ångström exponent data fall within one uncertainty unit of the 1:1 line (data not shown). Generally speaking, at least 70% of all AOT data compare within one uncertainty unit of the value from another instrument, with the best agreement between the hand held instruments. With its high uncertainty values, the Ångström Exponent comparisons are even better, at 90% or more. Other problems, such as sun pointing for the Microtops II, were resolved by modifying the measurement protocols³⁴ and uncertainty analysis performed for each instrument. Uncertainty values were computed and archived for each AOT and Ångström exponent measurement^{32, 35-37}. Computation of the Ångström exponent, which expresses the spectral character of the AOT values measured by sun photometers, was standardized (the Project's method used multiple bands and a linear fitting routine to paired wavelength and natural logarithm of AOT values). The Ångström exponent is the negative slope of this fit. This Ångström exponent calculation method uses a recursive routine that makes an analytical computation of uncertainty impossible. To account for this, an Ångström Exponent calculation method was devised that incorporates the individual AOT uncertainties and the Chi-square error to determine an Ångström exponent uncertainty.

Calibration Round Robin

Two kinds of activities were performed by the Project to further ensure the adequate quality of *in situ* data. First, as mentioned, measurement protocols were developed, and their usage by the science community encouraged. Second, calibration round-robin intercomparison experiments were conducted. The first SeaWiFS Transfer Radiometer (SXR) was built for the SeaWiFS Project to verify and compare measurements of spectral radiance at six discrete wavelengths in the visible and near infrared³⁸. The SXR is currently used to compare these sources to standards of spectral radiance maintained at the National Institute of Standards and Technology (NIST). The SIMBIOS Project had a second copy of the SeaWiFS Transfer Radiometer (SXR-II) built for use in the calibration round robin. This unit supplemented the first unit and was designed for easier travel. NASA personnel executed the first SeaWiFS-SIMBIOS Intercalibration Round-Robin Experiment (SIRREX-6) from August 1997 to February 1998. In SIRREX-6, four common field instruments (Satlantic in-water radiometers) were taken to nine separate laboratories and tested using the laboratories' standards and procedures. Two of the sensors were seven-channel radiance heads and two were seven-channel irradiance heads. The calibration and data reductions procedures used at each site followed that laboratories' normal procedures. The reference lamps normally used for the calibration of these types of instruments by the various laboratories were also used for this experiment. Project personnel processed the data to produce calibration parameters from the various laboratories for comparison. These tests showed an overall agreement at better than the +/-2% level⁹. The SIRREX-6 was followed by the SIMBIOS radiometric intercomparison experiments (SIMRIC-I and II) in 2001 & 2002^{6,10-11}. The purpose of these round-robins was to: 1) verify that all laboratories are on the same radiometric scale; 2) detect and correct problems at any individual laboratory in a timely fashion; 3) encourage the common use of calibration protocols; 4) identify areas where the calibration protocols need to be improved; and 5) document the calibration procedures specific to each laboratory. The participating laboratories included academic institutions, government agencies and instrument manufacturers that either directly or indirectly contributed to SeaBASS. They were, in alphabetical order: Biospherical Instruments Inc.; HOBI Labs Inc.; ICES at the University of California, Santa Barbara; MOBY Project of Moss Landing Marine Laboratories; NASA Code 920.1, Goddard Space Flight Center; NASA Code 972, Wallops Flight Facility; Naval Research Laboratories, Washington; Satlantic Inc., Canada; Scripps Institute of Oceanography, University of California, San Diego; University of Miami; University of South Florida, St. Petersburg. The SXR-II was calibrated on a yearly basis at NIST, in the Spectral Irradiance and Radiance Calibration with Uniform Sources (SIRCUS) facility. The radiometric stability of the SXR-II between NIST calibrations was monitored by the portable light sources the SeaWiFS Quality Monitors (SQM), the OCS-5002 from YES, Inc., and the SQM-II from Satlantic, Inc.) The radiances produced by the laboratories for calibration were measured in the six SXR-II channels from 411 nm to 777

nm and compared to the radiances expected by the laboratories. Typically, the SXR-II measured radiances differed from the radiances expected by the laboratories by less than 2%. This level of agreement is satisfactory. In some cases, larger deviations were found and tracked to issues like improper baffling, incorrect setup of the light sources, or deterioration of the main calibration bulb of the respective laboratory. Several issues were identified, where the calibration protocols needed to be improved, especially the reflectance calibration of the reference plaques and the distance correction when using the irradiance standards at distances greater than 50 cm.

6. CONCLUDING REMARKS

The calibration and validation programs for individual missions (both domestic and international) had a wide range of approaches and methodologies, making international cooperation imperative to ensure high quality climate data. The SIMBIOS Project and Program is a success story on how to tackle these issues while engaging the ocean color community. The achievements were certainly due to the operational configuration (Figure 1) and to the engagement of project staff with the science team. Over the past several years, a set of key resources were developed: 1) a comprehensive *in situ* bio-optical database; 2) a program to evaluate different atmospheric correction algorithms; 3) a program to link the calibrations of individual ocean color satellite instruments; 4) a program (including cross-calibrations and measurement protocols) to develop a consistent *in situ* calibration and validation data set for the satellite measurements; 5) a model for funded collection of *in situ* data, including rapid turnover; 6) alternate algorithms to convert radiometric measurements to derived geophysical products; and 7) alternate methods to combine ocean color measurements from different sources into a single data set. Our hope is that the organizational structure, lessons learned, and knowledge achieved by SIMBIOS will benefit future ocean color programs.

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