

The Proposal for the NASA Sensor Intercalibration and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Program, 1995

*Charles McClain, Wayne Esaias, Gene Feldman, Watson Gregg, and Stanford Hooker
NASA Goddard Space Flight Center, Greenbelt, Maryland*

Robert Frouin, Scripps Institution of Oceanography, University of California, San Diego, California

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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Preface

This technical memorandum is the original proposal submitted to NASA Headquarters in May 1995 for an ocean color satellite cross-calibration, product validation, and data merger program. The proposal was peer-reviewed and approved in FY96 and the program, now known as the Sensor Intercomparison for Marine Biological and Interdisciplinary Ocean Studies (SIMBIOS), formally started in FY97. SIMBIOS is in its second 3-year phase and is considered by NASA Headquarters to be part of its long term strategy for the Earth sciences. We are publishing the original plan because it outlines the SIMBIOS program strategy which is now in place and the original plan needs to be in a form that can be cited. A brief background of how the SIMBIOS program was conceived and established is included below. Beginning in 1998, the SIMBIOS Project has documented its activities and achievements in annual reports which are also published as NASA technical memorandums.

The need for an international ocean color calibration and validation activity was conceived in 1994 as a result of a NASA management review of the agency's strategy for a global time series of ocean observations. At that time, the NASA ocean color flight manifest included two data buy missions, SeaWiFS and the Earth Observing System (EOS) Color sensor, and the Moderate Resolution Imaging Spectroradiometer (MODIS), scheduled for flight on the EOS AM in 1998 and PM in 2001, and the Multi-angle Imaging Spectroradiometer (MISR) on EOS AM. Robert (Bob) Kirk (study manager) and I (project scientist) had been spent considerable effort on examining mission scenarios for EOS Color, including integration on Landsat-7 to reduce cost, because of the slips being encountered with SeaWiFS. However, with the delay of SeaWiFS and an uncertain launch schedule, it was not clear that EOS Color was needed to fill a potential gap between SeaWiFS and MODIS, especially when five additional ocean color systems with similar global capabilities [the Ocean Color and Temperature Sensor (OCTS), Japan; the Global Imager (GLI), Japan; Polarization and Directionality of the Earth's Reflectance sensor (POLDER)-1 and -2, France; and the Medium-Resolution Imaging Spectrometer (MERIS), European Space Agency] and several other non-global missions by Argentina, Germany, Taiwan, India, Korea, the U.S. Navy, and the People's Republic of China, were planned for launch during the late 1990s. 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 be associated with each mission and that combining ocean color data from this array of independent satellite systems to form consistent and accurate global bio-optical time series products would be a challenge. 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 program. NASA/GSFC was directed by Dr. Charles Kennel, the NASA Associate Administrator, Office of Earth Sciences, to develop a plan for submission to NASA HQ by May 1995.

As a result of the directive from NASA/HQ, the ocean color group at NASA/GSFC (the GSFC authors of this document) organized an international workshop in February 1995 at the University of Miami Rosenstiel School for Marine and Atmospheric Sciences. The objective was to develop a conceptual plan for the program. After the Miami meeting, I assumed the responsibility of organizing a proposal for NASA's contribution to the international effort. The plan was completed and submitted in May, as requested by NASA Headquarters, and was subsequently peer-reviewed. Approval was not automatic and Dr. Robert Frouin (the NASA ocean biogeochemistry program manager at the time) and I continued to work on orchestrating support for the program and imple-

mentation approach. This involved over a dozen briefings to GSFC management (Codes 100 and 900), NASA Headquarters (Code Y), the Committee on Earth Observation (CEOS) calibration and validation working group, the Intergovernmental Oceanographic Commission (IOC), the EOS Interdisciplinary Working Group (IWG) oceans panel, and other U.S. agencies.

The plan was approved in early FY96 and a NASA Research Announcement (NRA) was released in July, 1996. A SIMBIOS Project Office was established at the NASA Goddard Space Flight Center (GSFC) in January 1997 and is collocated with the SeaWiFS Project Office. The initial SIMBIOS plan was scoped for five years (1997-2001) and included separate support for a science team (NRA selections) and the project office. Dr. James (Jim) Mueller (San Diego State University) acted as an interim project manager at NASA/GSFC under a one-year assignment to assist in getting the project office organized and the science team contracts negotiated. I requested this arrangement because SeaWiFS was approaching launch readiness and I was serving as the calibration and validation manager and the project scientist at the time and could not devote sufficient time to SIMBIOS. I advised Jim in a project scientist capacity and did replace him as project manager after his one-year tenure.

In parallel to the NASA SIMBIOS program planning, the international effort was being organized. The initial meeting was held in Vittoria, British Columbia during September, 1995. As a result of the recommendations from that meeting, the International Ocean Colour-Coordinating Group (IOCCG) was formed. The IOCCG presently operates under the leadership Dr. Trevor Platt (Bedford Institute of Oceanography). The NASA ocean biogeochemistry program manager serves as the NASA representative to the IOCCG. The IOCCG meets one or two times per year and is generating a series of special reports on topics essential to the coordination of the international ocean color community. The SIMBIOS program was renewed in FY00 for a second 3-year period and a new science team was selected. I also stepped down as project manager in late FY00 as was replaced by Dr. Giulietta Fargion. Since 1994, the Modular Optoelectric Scanner (MOS, a German instrument on an Indian satellite), SeaWiFS, POLDER-1, OCTS, the Ocean Color Imager (OCI, Taiwan), the Ocean Color Monitor (India), the Ocean Scanning Multispectral Imager (OSMI, Korea), and MODIS (EOS AM, now called Terra) have been launched. In 2002, it is expected that MODIS (EOS PM, now called Aqua), MERIS, GLI and POLDER-2 will be launched. Thus, the decision to replace EOS Color with SIMBIOS has proved to be a wise one.

Charles R. McClain

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BACKGROUND

As a result of the Earth Observing System restructuring exercise during the last half of fiscal year 1994, the EOS Color mission which was scheduled to be a data buy with a 1998 launch was reconsidered. The initial response to the restructuring was to cut the EOS Color mission costs by placing the instrument on Landsat-7. This option reduced the mission cost by more than one-half and was shown to be technically viable, but was unacceptable given the already ambitious Landsat launch schedule and tight budget situation. An important factor in this decision was the number of international ocean color missions scheduled for launch over the next five years. As a result, NASA GSFC was tasked by Dr. C. Kennel to consider alternative flights of opportunity (none have been identified) and to develop an ocean color satellite calibration and validation plan for multiple sensors.

The objective of the activity is to develop a methodology and operational capability to combine data products from the various ocean color missions in a manner that ensures the best possible global coverage. The program will be called the Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) project coined from the term "symbiosis". In February, GSFC convened a three-day international workshop at the University of Miami Rosenstiel School of Marine and Atmospheric Sciences to begin the formulation of an international calibration comparison and product merger program. The plan outlined herein builds on the deliberations of that workshop and addresses issues on sensor calibration, product validation, data merging, data processing, interagency and international coordination and program implementation. The plan spans FY95 through FY99.

INTRODUCTION

The marine biosphere is an essential component of the Earth system which helps maintain conditions crucial for life on the planet. It directly provides about 20% of the food and half the O₂ used by humanity. The oceans, especially coastal waters, are important resources for humanity beyond food and respiration needs, including transportation, energy and recreation. Nearly half the global population resides in coastal regions, and the coastal biosphere is increasingly impacted through anthropogenic activities, both intentional and accidental. The marine biosphere influences weather and climate through the ocean heat budget, carbon cycle, and biogenic production of radiatively active trace gases. The world ocean, by far the largest reservoir of carbon on Earth, is a net sink for atmospheric carbon dioxide, and the marine biosphere, in particular, the phytoplankton are responsible for the uptake of carbon by the ocean.

Quantifying many of the roles of the marine biosphere in Earth's system and predicting how components of the marine biosphere will respond to environmental changes on global and regional scales has been extremely difficult. The distances involved are immense, the internal linkages are highly complex, important sources of variability exist on all scales from meters to thousands of kilometers, and sampling is both difficult and expensive. The ocean and its biosphere are constantly changing in response to atmospheric and radiative forcing, and it is virtually impossible to obtain synoptic or long term views of ocean physics and biology using traditional means, e.g. ships, moorings, aircraft, and underwater vehicles.

Satellite ocean color observations provide a crucial insight to the marine biosphere because of their capability to quantify certain fundamental properties on a global basis. These properties are (1) the optical attenuation length, which controls the depth of solar light penetration and heating and the depth at which photosynthesis can occur, (2) the abundance and distribution of plant pigments which is a surrogate for the biomass of marine phytoplankton and (3) the concentration of colored dissolved organic carbon. Results from the Nimbus-7 Coastal Zone Color Scanner (CZCS), a proof-of-concept mission, have demonstrated this repeatedly and conclusively. Results from the CZCS have been used to identify new key features of the global biosphere, such as ocean basin scale river plume dispersion patterns, the extent of equatorial upwelling and its variability, the richness of high latitude ecosystems, variations of coastal upwelling systems, and interannual variations in biosphere components related to the El Niño and Southern Oscillation. Estimates of biological productivity and marine biosphere CO₂ uptake, based on ocean color data, are being developed on scales ranging from daily/regional to interannual/global scales, but await the second generation sensors for implementation. The view of the marine biosphere provided by CZCS has revolutionized the way in which biological oceanographers view the oceans, and the way in which physical oceanographers view the marine biosphere. Increasingly sophisticated computer models linking the physical and biological components are being developed as a result.

These new tools are essential to refine our understanding of how the marine biosphere responds to global scale changes, and to quantify the feedback mechanisms between the marine biosphere and global climate and biogeochemical systems. Experience with the CZCS has pointed out needed improvements in instrumentation, algorithms and processing methodologies. These instrument improvements will result in a wider variety of data products and applications which will need quantification of product accuracies.

The success of the CZCS has led to several follow-on satellite sensor missions, within the U.S. (both federal and joint federal-private sector enterprises) and from the European Space Agency (ESA), Japan, Taiwan, Germany, and France. Basic instrument improvements over CZCS include better calibration stability monitoring, increased numbers of spectral bands and radiometric sensitivity, and the capability for collecting global coverage. Instrument improvements are being coupled with improvements in atmospheric correction algorithms and the quantification of derived ocean properties (e.g. distinguishing between chlorophyll-a and dissolved organic material). The latter example is important to improve the utility of the biomass surrogate for photosynthetic studies, and to quantify the distribution of an important ocean carbon pool, dissolved organic carbon (DOC), in biogeochemical studies.

Several of these proposed instruments are highly complementary and congruent in many important respects, but also exhibit significant differences in technical approach which have implications in algorithm and data product performance. Examples are the ability for MODIS, MERIS, and GLI to quantify the natural fluorescence of phytoplankton chlorophyll-a for physiological studies, and the exploitation of polarization fields by POLDER. Likewise, proposed methodologies and algorithms for the missions have significant differences. A major question is to what extent will the data be compatible. The need to develop a longer term, consistent time series of global bio-optical products is very important. This requires that the differences among the missions be resolved or explained at the level of major derived bio-optical products, with sufficient documentation to allow future scientists to relate their measurements to the ones obtained in the mid to late 1990s.

Because the ultimate comparison for ocean color is between the satellite derived products and data obtained via traditional techniques, both of which are very expensive to acquire, a well coordinated approach would make the most of collectively limited resources. Obscuration of the ocean due to clouds results in a major loss of data for any given mission, and combining data from several missions will significantly improve the ability to capture short term changes in the ocean.

The desire to make best use of the scheduled missions and to provide NASA with short term guidance in light of the deferral of the SeaWiFS follow-on (EOS COLOR) resulted in the NASA workshop on Multisensor Ocean Color, which reviewed the current plans for the major missions, and suggested an approach for implementing greater international coordination involving the Committee on Earth Observations Satellites (CEOS) and the International Geosphere-Biosphere Program (IGBP). The free exchanges of ideas and plans presented at the meeting have been used to develop this first-order plan. It outlines an approach to develop an international context for joint data analysis of the various ocean color missions. To provide short term guidance for NASA, this report provides an immediate implementation program that will be generally consistent with plans at the national and international levels as those plans become more mature. Hopefully, it provides a useful framework for developing a well coordinated plan, both at the national and international levels.

PLAN OVERVIEW

Between 1995 to 2001, there are seven missions scheduled for launch that are capable of providing routine ocean color coverage of large portions of the global ocean. In addition, there are four others of a more experimental nature that provide limited coverage. Figure 1 presents the mission time lines and Table 1 provides information on sensor and coverage characteristics. The CZCS is in-

cluded in Figure 1 because it provides a reference data set for global change studies. Because of the many algorithm improvements developed since the global CZCS processing was initiated in the mid-1980s, a reprocessing effort will be incorporated into this program. It should be noted that the primary instruments to be used for developing global data sets are SeaWiFS, OCTS, POLDER, MODIS (AM and PM), MISR, MERIS and GLI. The products from the other missions (ROCSAT, UVISI and the two MOS sensors) will be tracked and evaluated, but are not considered as key data sources for a combined global data set. The objective of this activity is to develop a methodology and operational capability to combine data products from the various ocean color missions in a manner that ensures the best possible global coverage. It incorporates aspects of instrument calibration, algorithm development and evaluation, product merging, data processing and interagency and international coordination. The program is scoped to accommodate the processing of large quantities of level-1 (calibrated), -2 (derived quantity) and -3 (space or time averaged) data from multiple missions in order to provide the best possible global bio-optical data products. Many of the topics and approaches outlined in this plan have been previously identified by Abbott et al. (1994) who make many very specific recommendations which are considered here.

As described in the Introduction, the biological processes to be studied using satellite ocean color observations occur over a broad range of space (meters to global) and time scales (hours to years) and some processes simply cannot be adequately sampled by a single instrument because of cloud cover, sun glint and orbit/swath limitations. As an example, Figure 2 provides an analysis of the 4-day coverage obtained from various combinations of one and two sensor coverage scenarios which clearly demonstrates the advantage of having at least two sensors in orbit simultaneously, especially at low latitudes. Given the desirability and likelihood of simultaneity in coverage, the challenge is to establish confidence and compatibility in the products in order to merge them into an integrated level-3 product.

The objectives of the proposed plan are (1) quantify the relative accuracies of the products from each mission, (2) work with each project to improve the level of confidence and compatibility among the products, and (3) generate the merged level-3 products. Therefore, the plan encompasses both experimental and operational requirements with links to all the missions, but has a separate management and facility structure which will be discussed in the section on plan implementation. The intercomparison program performs many functions similar to those being performed by each individual mission (calibration, validation, quality control, algorithm development and data processing; McClain et al., 1992), but does so by integrating information from each project, augmenting activities where appropriate and providing feedback to each project. These activities are organized into five basic components which form the core of the U.S. ocean color multimission comparison program. The components are calibration, validation, data merging, data processing and interagency - international coordination. All components are connected (and in some cases overlap) and each will be discussed in the following sections. Figure 3 illustrates the process of product development, assessment and refinement which is central to the intercomparison program. Also, because various terminologies are commonly used to loosely refer to different aspects of satellite calibration, validation and product generation, Appendix A provides definitions of these terms to avoid confusion.

MISSION CALIBRATION COMPARISON

The calibration program consists of six activities:

- (1) laboratory calibration and characterization of satellite and in situ instruments,
- (2) on-board calibration methodology development and data analysis,
- (3) in situ radiometer calibration services for NASA supported investigators,
- (4) vicarious calibration of the satellite sensors,
- (5) post-launch initialization of the satellite sensor calibration and
- (6) the development and maintenance of an instrument calibration data archive.

The primary purpose of the calibration activity is to reduce measurement error by identifying and characterizing true error sources such as (1) real changes in the satellite sensor and (2) problems in the atmospheric correction algorithm, and to differentiate these errors from natural variability in the marine light field. A complementary activity, shared with the validation program, is the continued refinement of measurement protocols which specify how in situ radiometer measurements are to be collected, both in the laboratory and in the field (Mueller and Austin, 1992 and 1995).

The Calibration and Validation Paradigm

To put these activities in the proper perspective, Figure 4 depicts the radiometric paradigm that defines the scope of the calibration program and incorporates a variety of on-orbit and in situ radiometric observation scenarios that can be used to track a satellite sensor's performance. The ultimate goals of the calibration program is to (1) ensure internally consistent in situ radiometric observations for bio-optical algorithm development and vicarious satellite sensor calibration and (2) ensure the operational sensor calibration-operational atmospheric correction algorithm combination yield water-leaving radiances with a 5% accuracy in clear-water regions. Missions which have comprehensive programs for pursuing these goals are labeled "Meets Cal/Val Paradigm" in Figure 4.

The justification for the first objective is obvious, but the objective of the second is more complex. The primary products of an ocean color mission are the water-leaving (L_w) radiances and all other derived fields are estimated from them. The system of sensor calibration and atmospheric correction algorithms must provide accurate L_w 's. However, validation of the atmospheric correction algorithm falls under the purview of the validation element. Therefore, the strategy of the calibration program is to focus on regions where the optical properties of the marine atmosphere and ocean are well understood and homogeneous, i.e. where the errors in the atmospheric correction and the in situ optical measurements are expected to be minimal. These reasons, along with logistical considerations, are why the MODIS oceans team and the SeaWiFS Project selected Hawaii as the site for an optical buoy.

Calibration Round Robins and Community Support

Implementation of the calibration plan builds on the programs already initiated by the SeaWiFS Project and the MODIS oceans team. For the laboratory calibration activity, the emphasis will be on

continuation and refinement of calibration round robins (Mueller, 1993; Mueller et al., 1994) and data analysis round robins (Siegel et al., 1995). The results of the first three calibration round robins have underscored the importance of consistent and traceable calibrations of laboratory facilities and techniques. Future round robins will emphasize education, the periodic rotation of the SeaWiFS Transfer Radiometer (SXR) through key calibration facilities and specialty topics such as solar-based plaque calibrations.

Additional activities to be included in the calibration program which are associated with in situ observations are (1) a calibration service to the NASA supported marine optics community to help ensure high quality measurements and (2) the development of a field stability monitor. A calibration service has been supported by the SeaWiFS Project, but cannot be continued because of the scheduled reduction in the SeaWiFS budget. Most investigators do not have the facilities to calibrate and characterize their own instruments and must rely on either the manufacturer or another group to provide that service. By supporting a calibration service at a single facility, traceability is greatly enhanced and simplified while total cost is substantially reduced.

A related development initiated by the SeaWiFS Project is a field stability monitor being designed by Carol Johnson at NIST. The monitor will be used to track the relative calibration of a field radiometer between laboratory calibrations. This capability is especially important during long deployments and in harsh physical environments. Assuming that the design is viable, several copies would be purchased and loaned to investigators, particularly those conducting time series measurements where the radiometers are used frequently.

Satellite Sensor Calibration

Prelaunch and on-orbit calibrations (internal lamps, solar diffusers, lunar imaging) will be performed by each individual ocean color project. The role of the calibration program will be to review the prelaunch sensor calibration and characterization data and calibration algorithms (the algorithm that converts digital counts to radiance), review the results and methods of the on-orbit calibrations provided by each project, make recommendations on each, and, if necessary, reprocess the calibration data using alternative approaches. A close working relationship between NASA and Hughes Corporation has provided invaluable insight into the design and performance of SeaWiFS and MODIS, e.g. stray light and out-of-band response. Similar information must be available for other ocean color sensors. Coordination and data analysis at this level requires a dedicated effort.

The various post-launch calibration methodologies identified in Figure 4 are lunar, solar, high altitude vicarious (cloud reflectance and in situ observation schemes) and sea level vicarious. All provide unique information which contribute to an overall scheme that isolates various terms in the radiometric equation, and, ideally, allows error estimates to be assigned to the terms on the right side of the equation. Table 2 provides a break down of the advantages and disadvantages of each method.

The vicarious calibration program will augment the programs currently being funded by MODIS and SeaWiFS. To date, SeaWiFS Project has invested heavily in the development of the MOBY (Marine Optical Buoy) being deployed off Lanai, Hawaii. Future funding will only provide limited maintenance for MOBY. The dovetailing of SeaWiFS and MODIS field programs and algorithm development has been by design from the beginning of the SeaWiFS Project. However, some questions on calibration orbit dependencies will need to be addressed which the MODIS oceans team will not have the resources to investigate during the early phases of the SeaWiFS and OCTS missions. Orbit

dependencies are associated with thermal cycling of the platform and the instrument, especially as the thermal blankets on the instruments degrade. Limited-term experiments in the Southern Ocean and at high northern latitudes will be required. If SeaWiFS and OCTS are launched within a few months of one another, one set of experiments could be conducted to handle both missions. Assuming an experiment in 1996, the experiment should be repeated after MODIS is launched in 1998 or 1999.

The high-altitude vicarious calibrations include measurements of uniform, flat land or fresh, clear-water sites and cloud tops. The purpose of the measurements is to provide an independent in-flight calibration of the satellite sensor. The land or clear-water sites should be at elevations of >1000 m in regions of low aerosol loading. These sites must be sufficiently uniform over a large enough area to avoid the effects of stray light (Barnes et al., 1995) and electronic overshoot (Mueller, 1988) off nearby targets that are relatively bright. The primary measurements, with an airborne radiometer, will be of spectral radiances in the bands of the satellite sensor made simultaneously with the sensor's acquisition of an image of the scene. The radiometer must be highly stable with an uncertainty in absolute calibration of <2%, one sigma. For a bright land target, the recorded radiances will be over 90% of the top of the atmosphere radiance for most bands. The small correction for the residual atmosphere above the aircraft can be made accurately from a knowledge of the atmospheric pressure at the aircraft altitude and optical depth and surface reflectance measurements made at ground level. These quantities are used in a radiative transfer code to determine the correction, which is the atmospheric path radiance and ozone attenuation between the aircraft and the top of the atmosphere. Dry playa surfaces, observed under large solar zenith angles, will give radiances near the top of the dynamic range for ocean sensors. Even though the radiometric sensitivity of SeaWiFS, for example, will be reduced to 8-bit over this range, it will be quite adequate for accurate absolute calibration. Lake surfaces will give at-satellite radiances similar to those over the oceans (reduced Rayleigh and aerosol radiances). Cloud-top reflectances offer a statistically huge and frequent (daily) sample, but have been shown to be more useful in providing relative calibrations as a function of time than in yielding accurate absolute calibrations and, therefore, complement the solar diffuser observations.

Figure 5 shows likely sites for calibration activities. From the discussion above, the Hawaii, High Altitude, Southern Ocean and High Latitude (Northern Hemisphere) sites would serve as calibration sites with all but Hawaii being short term experiments. Other sites such as the MAST and YBOM sites (Figure 7) are classified as validation sites because they are situated in relatively turbid water. The BATS (Bermuda Atlantic Time Series) site could serve both purposes if the present sampling strategy using funding from the SeaWiFS Project and NSF is maintained. However, it is unclear that support for optical measurements at the BATS site will continue beyond 1995 and it is at a similar latitude as Hawaii, so it is considered to be primarily a validation site. Also, at high latitudes, multiple observations per day from each instrument are possible which allow for direct comparison of derived products.

Mission Initialization

With each launch of an ocean color mission, an initialization experiment should be executed shortly after the instrument cover is removed and data collection starts. The purpose of the initialization experiment is to determine if the instrument performance changed after the prelaunch calibration. Changes can occur during environmental testing of the integrated spacecraft and during orbit raising. The experiment establishes the initial adjustments to the calibration equation coefficients required to

reproduce the observed water leaving radiances. Atmospheric measurements of optical thicknesses and sky radiances are used to ensure accurate radiative transfer model estimates of the expected satellite total radiance. Figure 1 shows when initialization cruises will be conducted. Note that the experiments for SeaWiFS and MODIS/MISR are already funded, but those for OCTS/POLDER, MERIS and GLI are not. Initialization cruises are only planned for missions that can contribute substantially to a global data set. Support of other missions will be available only as the opportunity arises in conjunction with the primary mission launches.

Calibration Data Archival

Finally, all calibration related data must be archived. The SeaWiFS Project has undertaken the development of a data archive and retrieval system called SeaBASS (SeaWiFS Bio-optical Archive and Storage System; Hooker et al., 1994). It is proposed that this system be expanded and refined to incorporate data for the other ocean color missions and be housed within the project. Presently, SeaBASS data sets include data from the calibration round robins, the SeaWiFS prelaunch calibration and characterization data and a large number of bio-optical data sets for product validation and algorithm development. The SeaWiFS Project will not be staffed at a level to accommodate multiple missions and an expanded international round robin program. Thus, SIMBIOS must assume responsibility for handling the expanded archive responsibilities.

DATA PRODUCT VALIDATION

General Considerations

The framework for validation incorporates principal investigator-led data collection and analysis studies and SIMBIOS project field data archival and satellite data processing activities. Much of the at-sea data collection, and analysis of the results, will be performed through investigators selected by an NRA. These data collection activities are most cost effective if existing and proposed programs are augmented, rather than initiating new and independent programs. An example of this is the SeaWiFS Project's support for improved bio-optical measurements at the BATS site, which is an augmentation to NSF grants.

Validation is the process of determining the spatial and temporal error fields of a given biological/geophysical data product. As a simple example, a level-3 global image of chlorophyll-a might have a companion global image of the rms error in the estimate of chlorophyll-a for the same time period. This error field might be generated with selected in-situ data, extrapolation models, and other data or models. It can be viewed as a spatial realization of the error budget bottom line. This assumes that the accuracy of the product will not be uniform or constant due to spatial and temporal impacts on the algorithm, surface conditions, viewing geometry, instrument response, calibration accuracy, atmospheric conditions, etc. Not all products may have sufficiently defined error budgets at launch to produce an error field, so validation may be qualitative at first.

The robustness of the validation program is primarily a function of the quality, sampling, and coverage of the data used for comparison. An important part of validation is also internal consistency of the data. A third part of the validation process might involve comparison with modeled surrogates. Comparison of satellite derived values with real in situ values is the basis for determining the accuracy of a data product in extended ranges. The uncertainty field is comprised of uncertainty in instrument characterization and calibration, in the comparison data, sampling differences between

comparison data and derived products, inaccuracies in the algorithm, and inaccuracies of input data products. Biases in these contributing errors might have very different impacts on product utilization than would random errors or noise, in so far as analysis of temporal and spatial trends is concerned. Identification and elimination of biases between regions and between mission data sets is a primary objective of the SIMBIOS program.

If the ocean biological pump is to be considered to be in steady state, then regional increases in productivity (e.g. the tropical Pacific) must be exactly balanced by decreases elsewhere on an annual basis. Separating these variations, which may be small in magnitude but extensive spatially, from regional biases is a challenge. In some cases where the physics is very simple and predictable (all sources of error easily determined and predicted), validation at a few points and times may be sufficient to provide good estimates of errors in all places and times. Such might be the case where the product is a direct or simple transform of the observed property, such as brightness temperature. In other cases, notably chlorophyll-a and especially the rate of primary production, the relationship between the derived property and the remotely sensed quantity (radiance) is much more complex and dependent upon the response and interactions of a large number of independent variables. In these cases the temporal and spatial variability of the product, fields of other variables, and algorithm error budgets are poorly known and the breadth of the validation process must be considerably larger and ongoing. The validation program must weigh the accuracy of the data product required to address major EOS goals and objectives in order to properly allocate resources.

Given the range of geographic and temporal variations, and the inherent variability of ocean biological measurements at small scales, large numbers of comparison matches are required to establish the error fields. Quantifying the number is difficult, but a simple analogy with SST requirements would indicate that numbers in the thousands may be required.

Every mission has a minimal validation program, but resources do not allow for complete validation of products over the full range of oceanic and atmospheric conditions expected to be encountered globally. Some are tuned to regions and sensor of interest. Major benefits of a well coordinated international approach, and sharing of validation data (in situ/ancillary) immediately increase by about 10-fold the spatial and temporal coverage of error field determination and enable comparison of data products. An international program is needed to provide mechanisms for increased participation and sharing of responsibilities by non-mission programs, and can be useful in obtaining observations in remote, critical areas in a cost effective manner.

Focused field expeditions provide limited and discontinuous time series of important variables, but are required for understanding regional and small scale processes and dependencies. Global inventory cruises can provide unique correlative data in very poorly sampled regions. They provide necessary supporting data for extrapolation of regional understandings based on satellite derived fields to the global ocean. Stationary time series provide information on the temporal domain, but can be obtained only for a few locations. Presently, bio-optical time series at BATS and the MOBY site are in oligotrophic waters.

Data collected for validation of products from sensor A can generally be used to validate products from sensor B, i.e., there is very good coherence in data products between missions. Some differences are very complementary (e.g., POLDER and OCTS), but will require allowance to be made for pixel size and differences in band characteristics. The choice between reporting radiances in contrast

to reflectance is not a big issue. Many algorithms are now posed to operate upon reflectance, or normalized radiances. Calibration accuracy goals for SeaWiFS relate to comparisons with water leaving radiance, since radiance is the basic physical property that is measured, and the accuracy of techniques for making reflectance measurements at sea has not been adequately established.

A coordinated data collection system like NOAA/WMO SST buoy network or Dobson/UV monitoring network does not exist for ocean biogeochemistry. Several buoy/mooring systems for meteorology or physical oceanography are in place, e.g. TOGA/TAO and the National Data Buoy Center (NDBC) meteorological towers and buoys. A study is underway to examine the feasibility of adding optical instruments to NDBC towers and buoys. Also several research optical moorings have been developed which could fill important roles in the coastal zone and open ocean.

Basic protocols for performing many of the bio-optical measurements needed for both calibration and validation have been written (Mueller and Austin, 1993 and 1994; Wernand, 1994). These should be reviewed with respect to application to all sensors and products of importance. Existing protocols for making primary productivity measurements, and extrapolating from short term and deck incubations need to be reviewed and established by the scientific community.

Validation of Water-leaving Radiances

Validation of atmospheric correction means quantification of the expected uncertainty associated with the retrieval of the water-leaving radiance from measurement of the total radiance exiting the ocean-atmosphere system along with measurement or estimation of auxiliary data required in the retrieval process, e.g., surface wind speed, surface atmospheric pressure, total column ozone concentration. For a proper validation, this quantification must be carried out over the full range of water-leaving radiance values (determined largely by the phytoplankton pigment concentration in Case 1 waters) and the full range of atmospheric types expected to be encountered in the retrievals.

Validation of the basic aerosol correction

There are several components required in the process of atmospheric correction [See Gordon and Wang (1994) for a description of the SeaWiFS/MODIS atmospheric correction algorithm]. The most important is the removal of the aerosol component from the sensor-measured radiance. Unlike the earlier CZCS algorithm, in the SeaWiFS/MODIS era, accuracy requirements force addressing the issue of multiple scattering in a quantitative manner. Assessing multiple scattering is accomplished by examination of the aerosol component of the radiance in the near infrared, where the water-leaving radiance is negligible except in very turbid coastal waters, to select an aerosol model for extrapolating the result into the visible. The models currently employed in the prototype MODIS algorithm (the SeaWiFS algorithm) are those provided by Shettle and Fenn (1979). These aerosol models were developed to predict atmospheric transmission and, although widely used, have not been validated for the radiative transfer computations required in remote sensing. Such a validation is the subject of intense research at the present time and will be on-going during the initial phases in the validation of SeaWiFS imagery. As this validation is incomplete at present, it will be addressed in this plan.

At the very basic level, sensors utilizing algorithms based on the use of aerosol models must be validated initially under the most favorable of conditions, i.e., a relatively clear atmosphere as would be found over the open ocean free of land and anthropogenic sources. In such a region, the aerosol is likely to be locally generated and reside in the marine boundary layer. Also, the within-pixel variability of the water-leaving radiance will be small if the validation site is properly chosen. Only

whitecaps and residual sun glitter are required to be removed in order that conditions satisfy those assumed in the development of the correction algorithm, i.e., essentially a relatively clear two-layer atmosphere with aerosols in the lower layer. Such a location is also ideal for vicarious calibration, and for initialization, the initial post-launch adjustment of the sensor calibration based on a complete radiative transfer model of the air column. Under these conditions, the error in the water-leaving radiance due to the aerosol removal should be small, and specifying this component error field under these conditions relatively simple. Errors due to whitecaps and sun glitter may make a significant contribution to the overall error and such a location would be ideal for specifying the error fields due to these processes.

A validation program therefore includes an experiment in a region that is expected to be dominated by a locally-generated aerosol and over waters with a low pigment concentration, e.g., the waters off Hawaii. Along with the basic aerosol correction, such a region will also be essential for validating the whitecap and sun glitter removal algorithms. If permanent, such a site would also be invaluable for vicarious calibration of individual sensors and calibration comparison of multiple sensors

Strongly absorbing aerosols

There are two situations in which the atmospheric correction algorithm as presently formulated may not retrieve the water-leaving radiances within acceptable error limits: situations in which the aerosol is strongly absorbing, but the absorption is relatively independent of wavelength (urban aerosols transported over the oceans); and situations in which the aerosol is absorbing with a wavelength-dependent absorption (desert dust transported over the oceans). The reason for the difficulty is that near infrared measurements of the spectral radiance due to absorbing aerosols are not as good an indication of the aerosol influence in the visible as in the case of nonabsorbing or weakly-absorbing aerosols. This is particularly true in the case of desert dust for which the aerosol absorption properties can change considerably from the near infrared to the visible. Therefore, it is important to perform validation in regions and times where significant amounts of absorbing aerosol are expected to be present over the water. In the case of urban pollution, an ideal location is the Middle Atlantic Bight during summer (excellent logistics as well). For desert dust there are two important regions: (1) the North Pacific (Gobi desert influence) and the tropical North Atlantic (Saharan desert influence). The validation plan, therefore, includes measurements in these regions using both ship and sun-photometer stations.

High latitude corrections

It is also necessary to validate the water-leaving radiances at high latitudes in which the curvature of the earth can be important because of the possibility of very large solar zenith angles. Ding and Gordon (1994) have predicted that for sun angles greater than 70-75 degrees, significant errors in atmospheric correction are possible, if the atmosphere is assumed to be plane parallel. They provided a correction method, which unfortunately cannot be validated using the CZCS because of its insufficient radiometric sensitivity. The implementation plan has included some high latitude activities, and will solicit others.

Turbid waters

Under conditions where appreciable water-leaving radiance exists due to high in-water scattering, errors in the atmospheric correction may be large and undefined. These situations occur in the open ocean in coccolithophore blooms, and especially in coastal waters with high sediment loads. It is important to perform validation measurements in these regions to assess the degree of inaccuracy,

and to provide information for making improvements or applying corrections. Improvements will result in better performance of the in-water algorithms in turbid waters. The implementation plan addresses this need.

Effects of bright targets

Instruments with multiple detectors per focal plane are susceptible to ghosting and optical scatter while viewing regions of high contrast (like dark oceans near bright clouds and, in the near-infrared, bright terrestrial vegetation). The nature of the effect is particularly troublesome for ratios of bands in different locations on a focal plane, and will affect both water-leaving radiances and bio-optical algorithms separately. Partial corrections for these effects are planned as part of the level-1 or -2 data processing for SeaWiFS and MODIS. The magnitude of these effects in the OCTS and other sensors has not been established. Instruments must be well characterized in order to define their response and to provide a basis for correction algorithms. The zeroth-order correction envisioned is to simply mask (or denote as incorrect) the region involved. The ability to use the data close to the coast may be greatly diminished, and large amounts of data may be masked near clouds without such correction and validation. The accuracy of bright target and stray light corrections planned for at-launch algorithms for the NASA sensors must be verified both by image analysis techniques and field measurements. Verification of these procedures could proceed in coastal regions as well as for clouds over the open ocean. These should include transects up and down scan from land with various land covers, and regions of clouds. Measurements performed with a combination of surface and airborne imaging observations are suitable and will also provide a basis for improvements to the corrections. It is recommended that these activities be accomplished by investigators selected through the NRA.

Whitecaps and sun glitter

Other major contributors to the radiance measured by a satellite radiometer include the whitecaps and sun glitter. The algorithm estimates their contribution based on the wind speed and direction. Thus, it is important to measure their contribution along with the wind speed and direction during validation exercises. These effects should be measured with radiometers or imagers from ships and aircraft, along with wind speed and direction and significant wave height. Data collected in many expeditions will serve for validating the corrections and masking of glitter. Special studies are required for whitecaps.

Sun Photometer Network

Figure 6 indicates present and planned sun photometers that are located near coasts or on islands which will provide data required for validation of atmospheric properties. Table 3 provides the location and name of the PI, and the observation period scheduled. Most of these are funded by other programs. The illustrated network provides good coverage at mid latitudes and of Saharan and Gobi aerosol regions. The stations at La Jolla, Wallops, and the Dry Tortugas will provide for validation in coastal U.S. waters, and for aerosols that vary between predominantly maritime and continental depending on wind direction. A site in Hawaii is very crucial for the clear water vicarious calibration activity associated with MOBY. Coverage is sparse at high northern latitudes and for most of the Southern Hemisphere. SIMBIOS would provide for four additional instruments (three for assignment as time series stations and one to serve as a portable station in support of field studies) and maintenance of them. Additionally, support should be provided to Brent Holben for calibration and maintenance of the existing (and impressive) data base system.

The total number of sun photometers in use is much larger. These are deployed at various altitudes and are generally inland. Many are deployed only during focused field programs (e.g. BOREAS and SCAR). Some of these stations might prove useful for working with adjacent lakes. The intent here is to provide an on-going time series of coastal sites. Support of the 3 SIMBIOS sites (Hawaii, Wallops and La Jolla) will be through open solicitation, since cost depends on the ease of maintenance. These measurements should be continued for at least several years to establish confidence in the ability of the algorithms to handle major seasonal variations in atmospheric properties.

Data requirements

The fundamental data required for the validation of the normalized water-leaving radiance is obviously the normalized water-leaving radiance itself. Also, the data requirements are similar to those for vicarious calibration and initialization. In the multisensor era, because each sensor to be compared will have different spectral response functions, it must be measured spectrally. This quantity can be measured using ships, buoys, or drifters. In regions where significant horizontal gradients can be present (e.g., the Middle Atlantic Bight) it is also necessary to assess the within-pixel variability. This can be effected using ships and/or aircraft-borne sensors. Measurements of the normalized water-leaving radiance are usually made with nadir-viewing radiometers; however, it is known (Morel and Gentilli, 1993) that the water-leaving radiance can depend on both the viewing geometry and the solar zenith angle, i.e., the water-leaving radiance viewed at an angle of 45 degrees with the surface is not the same as that viewed at nadir. This effect must be considered for validation of any given sensor over its entire range of scan angles, but it becomes of paramount importance in the case of multisensor cross validation campaigns since each sensor will view the validation area with different viewing geometries. In such cases one must either make simultaneous measurements that can be used to correct for the effect (the complete subsurface upwelling radiance distribution (Voss, 1989)), or carry out additional research to sufficiently understand the bi-directional radiance distribution function (BRDF) of the normalized water-leaving radiance to be able to correct nadir measurements for the proper viewing geometry.

In many cases it is to be expected that the satellite-derived normalized water-leaving radiances will not agree with the surface measurements. In such cases it is important to understand what part of the atmospheric correction algorithm is at fault in order to facilitate algorithm "fine tuning." Since the major (and highly variable) component to be removed during atmospheric correction are the aerosols, it is important to make detailed measurements of the columnar aerosol optical properties as part of an over-all validation effort. Quantities to be measured include the spectral aerosol optical thickness and the spectral sky radiance, both close to (the aureole) and far from the sun. From such measurements, it is possible to obtain the columnar aerosol size distribution, aerosol phase function and aerosol single scattering albedo, an index of the aerosol absorption (King et al. 1978, King and Herman 1979, Nakajima et al. 1983, Wang and Gordon 1993, Kaufman et al. 1994). This data can be used to determine the applicability of the aerosol model selected by the algorithm for use in the atmospheric correction, and to provide a determination of the presence or absence of strongly absorbing aerosols. As described earlier, the correction algorithm is based on the assumption that all of the aerosol is located in the marine boundary layer. (Note that this may be changed based on experience derived from SeaWiFS imagery; however, the correction algorithm will of necessity have to be based on some "standard" vertical profile of aerosol concentration.) Thus, an additional possibility for degradation in the accuracy of the retrieved water-leaving radiances is the presence of significant quantities of aerosol in the free troposphere or the stratosphere. For instruments like MODIS, which have spectral bands capable of detecting stratospheric aerosol and thin cirrus clouds, the contamina-

tion due to the presence of these components will be partially removed; however, this will not be the case for less-sophisticated sensors, e.g., SeaWiFS. The simplest technique of detecting deviations from the assumed vertical structure of the aerosol is LIDAR, and such measurements, either ship-borne or air-borne, should be included in validation exercises. Such at-sea LIDAR measurements would also be extremely valuable in pre-launch algorithm development work to develop a climatology of aerosol vertical profiles over the oceans. Thus, the recommended aerosol-related measurements include measurement of aerosol properties by measurement of optical thickness and sky radiance from islands and ships using CIMEL type instruments, all sky cameras and/or aureolometers, and LIDAR measurements of vertical profiles.

Identification of key regions

Based on the discussion above regarding the possible reasons for problems with atmospheric correction, five general locations for validation are recommended. For the most part, these are also applicable to validation of bio-optical products.

- A. Middle Atlantic Bight (Urban aerosol, high reflectance waters, bright land)
- B. Sea of Japan and Equatorial Atlantic (Dust)
- C. Very high-latitude site (Earth curvature)
- D. Strong winds, e.g., trades (whitecaps, glitter; Hawaii)
- E. Southern Ocean (Aerosol models)
- F. Clear oceanic air (Aerosol models; Hawaii)
- G. Before and after bright targets (Hawaii, MAB, West Coast)

Validation sites for water-leaving radiance and bio-optical properties are shown in Figure 7.

Validation of Bio-optical Properties

Validation data collection should emphasize chlorophyll-a, pigment concentration, optical diffuse attenuation coefficient (K), primary productivity, coccoliths, suspended sediments and fluorescence. The validation program should provide for some collection of data for research products such as optical absorbance, as instruments and protocols for performing this measurement become more widely accepted. Collection of multiple parameters at each station are required only for complete data sets and for initialization, and for algorithm development where warranted. Data for single parameters, if made consistently, are still very useful and encouraged.

It is likely that measurements of pigment concentration and chlorophyll-a might be the most widely measured parameters. In the CZCS era, pigment concentration was the key variable used for vicarious calibration and initializing the atmospheric correction. It was also the primary in-water algorithm. In the present era more precise (<3% uncertainty) chlorophyll-a concentrations will be measured extensively because of the relative ease of making the measurement, and because of its importance for estimating phytoplankton biomass, water mass identification, and its relationship to productivity. Bulk pigment and fluorescence techniques are still very significant because they can be made continuously and from buoys.

The accuracy of validation products is important, but levels of accuracy can vary according to use. Chlorophyll-a measured along ship tracks, drifting buoys, or aircraft flight lines with a precision of 20% is useful in some regions which may be suspected of having a $\pm 100\%$ bias, for example. More precise measurements would be required when the values are used to validate algorithms or in

developing photosynthetic models. Collection of data for validation of specific products may be in order for special situations, like sediment concentration for geological studies.

In addition to the regions identified for validation of water-leaving radiance, validation of chlorophyll fields should also attempt to sample the world in a stratified approach. Variability in optical properties and packaging effects of the phytoplankton and other components of the hydrosol should be addressed. Variability is high in the coastal zone. River plumes present important sources of nutrients, sediments, and dissolved carbon, and phytoplankton concentrations tend to be higher along coasts. The majority of biological oceanographic sampling occurs in the coastal zone, so the number of observations is expected to be relatively high compared to the vast open ocean. Adequate validation must occur in all regions.

Primary productivity algorithms and validation

Currently, NASA is the only agency with a commitment for a standard primary productivity algorithm; other missions include this in the research/non-standard category. The current approach to development of primary productivity algorithms within NASA is shared within the SeaWiFS Science Team (as a research/post-launch product) and the MODIS Instrument Team (a standard at-launch product). Development of daily-weekly scale algorithms were specifically selected under the SeaWiFS NRA. The plan, developed before the extensive slips in SeaWiFS launch, was to develop a consensus productivity algorithm within the Primary Productivity Working Group (PPWG, a joint SeaWiFS and MODIS activity) using SeaWiFS data, and to have a robust algorithm ready for review within two years after the SeaWiFS launch (or by late 1995). Following approval, the SeaWiFS Project would implement the algorithm. The schedule for development of MODIS algorithms required full definition much sooner (late 1993), well before the community felt a good consensus could be reached given the multiplicity and breadth of approaches. An annual empirical algorithm was therefore defined for MODIS, with consensus of the PPWG, which would evolve to include the consensus daily algorithm as soon as possible within the framework of EOSDIS. This approach has been clearly identified in the MODIS Algorithm Theoretical Basis Documentation (ATBD) since 1993.

This approach needs revision to account for the long delay in SeaWiFS launch, primarily due to the decreased funds available for SeaWiFS team investigations required to develop, test, and validate various approaches for a daily primary productivity algorithm. At least two year's support following the launch of SeaWiFS or OCTS is required to obtain sufficient understanding of the various approaches. The present structure within the MODIS team is inadequate and inappropriate for such a major research activity involving multiple PI's. Therefore this development should continue under an NRA, although the field work could probably be narrowed to fewer investigations in consideration of the progress that has occurred.

The accuracy of primary productivity algorithms is very dependent upon accuracy achieved for several level-2 products including chlorophyll, diffuse attenuation, and PAR, as these are generally primary input variables. In addition, separate measurements of productivity are required for validation. Obtaining these measurements in a variety of water types should be a high priority for validation programs. In this case, the variability to be covered should strive to include ranges of biological conditions as well as the ranges of optical characteristics, namely temperature, nutrient concentrations, periods in the bloom cycle, population structure, zooplankton grazing stress, and iron limited

regions, and must be concerned with the depth distributions of the phytoplankton and diel variations within the ranges of satellite overpass times.

As discussed earlier, agreement upon protocols for measurements, including use of ^{13}C techniques and the pixel extrapolation issues, is an important early step which must be addressed, but should not preclude beginning a quality observation program. Many of the techniques have a wide if not universal acceptance by various members of the community.

Several SeaWiFS Science Team investigations are addressing the development of different types of algorithms, and many of these include field components. These investigations take place in a variety of water types, often in conjunction with JGOFS and other larger programs. Routinely such measurements are taken with clean techniques, and are accompanied by good measurements of K , chlorophyll, temperature, and incident irradiance. With attention to calibration, these measurements form a very acceptable suite for primary productivity derived from remote sensing measurements of chlorophyll at the present time. Research using spectral convolution techniques is also promising, but requires additional spectral radiance or irradiance measurements which should be encouraged, but not strictly required. It is very important that investigations of this nature continue after the launch of SeaWiFS, and be included in the SIMBIOS validation program. An objective for SIMBIOS is to include additional focused cruise validation sampling, as well as begin new productivity time series observations.

A time series of productivity in moderately high production waters is highly recommended. This will complement the JGOFS HOTS and BATS programs by extending the range of productivity values measured, but also assumes that NSF and IGBP commitment to the HOTS and BATS stations will not falter. Since variability tends to scale with chlorophyll concentration, a time series station in productive waters will also sample a range of biological conditions throughout the year. For the first several years, this test station will also serve as a site to compare methodologies leading toward the development of common acceptable protocols. These should include new methodologies, like pulsed fluorescence measurements for estimating photosynthetic parameters (P_{max}) required for the physiological-based algorithms as well as empirical algorithms. They should explicitly address uncertainties arising from intra-pixel variability of productivity (does it covary simply with chlorophyll?) and diel effects (to account for various satellite overpass times). Given the high variability in the data due to spatial effects, obtaining good information on diel effects will be difficult at a single station. Additional annual time series observations are required for annual empirical estimations, again in more productive waters.

A site off either the east or west U.S. Coast, convenient for a moderate size ship to sample bi-weekly to monthly, yet far enough (20 -30 km) offshore to avoid potential bright target and bottom effects should be considered. There are several sites with extensive knowledge associated with the region that would provide a useful context on intra-annual variability, such as the Gulf of Maine, the Mid Atlantic Bight, the CalCOFI area, and N.W. U. S. upwelling regions. Since there are on-going investigations by other agencies in these waters, cost sharing should be explored.

Crossing time differences

Merging of data from multiple missions also requires investigations of phenomena related to differences in time of sampling. These studies are generally not included in specific mission validation scenarios, because crossing time is generally dictated by engineering and cloud cover considerations,

not necessarily physiological and physical interaction concerns. These relate directly to merging data, and should be addressed in the NRA. Biological and physical variability has implications related to crossing time of multiple sensors. Accounting for effects of small scale spatial variability (intra-pixel) has always been a concern when making correlative measurements. Spatial averaging of ship data is usually used, and windows of acceptable time differences are usually on the scale of hours to a day. Typically validation measurements are performed in uniform and quiescent areas to avoid variability which complicates comparisons with satellite data. These present a special case in the coastal zone, where scales of variability are shorter due to the role of currents and the intrinsic rate of change. Collection of surface data in support of multiple sensors which are expected to have markedly different sampling times must take these effects into account, and also other effects which may present significant biases.

Effects of diel variations in chlorophyll/carbon ratios, photosynthetic efficiency, photodegradation of dissolved material, and vertical tidal induced mixing must be considered for the in-water algorithms. For example, time differences between sequential views of MODIS, OCTS, and SeaWiFS can range between minutes to hours (about 5 hours when MODIS PM is considered, and longer in the case of UVISI). This period can cover almost the entire range of vertical turbulent energy input from tidal currents, which is proportional to the cube of current velocity and peaks every 6.25 hours. In some estuarine and shelf situations the waters will transition from highly stratified to well-mixed in this period and can be advected 10-15 km during that time. Observations in both well-mixed and stratified conditions will be needed. Also, these data can be quite useful in exploring the coupling between physical and biological processes and for resource assessment in such regions.

Field activities

Plymouth Marine Laboratory/Atlantic Meridional Transect (PML/AMT): The RRS Sir John Clark Ross steams a meridional transect of the Atlantic every spring and fall to resupply the British Antarctic Expedition (BAS, see Fig 7). Dr. James Aiken of PML has arranged for along-track sampling and has proposed additional station time (two hours/day), although this is not yet received final approval. He has encouraged NASA participation. Extra days may be available to enable the transect to extend to 60° N (and perhaps with additional funds, to north of Iceland). Participation in this opportunity has high priority for several reasons:

- (a) It provides an excellent mechanism to perform calibration activities related to intra-orbit variations since the same instruments can be used at high northern and southern latitudes. This is especially important to establish whether there is any instrument bias involved in the significant differences between northern and southern hemisphere chlorophyll and productivity.
- (b) It transects 6 distinct oceanographic provinces, seasonally mixed N. Atlantic, N. and S. Atlantic central gyres, NECC/Amazon plume region, equatorial upwelling, and the Antarctic frontal regions.
- (c) The cruise track encounters several distinct aerosol types, including those in the N. Hemisphere, Saharan dust, and the more pristine S. Atlantic and offers an opportunity to address issues discussed earlier.
- (d) The cruise also transects the Southern Anomaly which might impact the performance of the satellites.
- (e) Coccolithophore rich waters will be experienced at both ends of the track.
- (f) The end points will be useful (but not definitive) for examining low sun angle effects on atmospheric corrections.

The plan is to participate in the two cruises per year for the duration of the project.

Support from the SIMBIOS Project will be for any additional ship time to extend observations, standard equipment, shipping and logistics, and food. P.I. participation for data collection and analysis will be solicited for investigations to complement those planned by Dr. Aiken's group, which is a SeaWiFS Science Team activity, including sun-photometry and profiles of apparent and inherent bio-optical properties on station. Dr. Aiken currently plans to carry out water sampling for bio-optical measurements and along-track radiometry for all relevant spectral bands. A formal agreement should be pursued with the British.

Participation in process studies: The third major activity is direct participation in JGOFS processes studies, including the Southern Ocean transect, and the planned North Atlantic Study which will follow that, by augmenting the JGOFS effort with additional ship days and personnel focused on validation of ocean color data from various sensors. Support envisioned includes additional ship time for cruise activities which would otherwise tax the berthing space required for JGOFS objectives, and for P.I. support for data collection and analysis both for the added cruise time as well as augmentation of other cruises. This will enable collection of basic validation and calibration data in the poorly sampled Southern Ocean. It will aid in removing any biases in the data due to high latitude effects on bio-optical properties of phytoplankton and water-leaving radiance algorithms, as well as providing another tie point for potential intra-orbit effects. A strong validation effort is especially important to provide a firm bio-optical context to the JGOFS process study, to enable extrapolation of results to periods and regions beyond the site of the process study. Similar arguments hold for the follow-on North Atlantic study.

Coastal experiments and time series: An additional category covers participation of NASA bio-optical and validation expertise in several important, on-going regional studies. Generically, however, additional support is warranted to add crucial observations which would not normally be performed as part of those studies, but which will greatly increase the usefulness of ocean color data within the studies. This will provide linkages to address region-specific effects in the standard ocean data products, provide validation data in variable and more turbid waters, and help in applying the regional results to a global perspective through the use of satellite data.

In the 1996-1997 time frame, NOAA, DOE and ONR will sponsor focused field studies in the Middle Atlantic Bight (MAB). These are DOE's Ocean Margins Program (OMP), ONR's Ocean Mixing and Light (OM&L) study, and NOAA's Land Margin Ecosystem Research (LMER) project in the Chesapeake Bay. These excellent coastal studies have commonality in deployment of a number of instrument moorings (with some optics for the first two), planned use of ocean color observations, and extended durations, even though their foci are quite different. The OMP program is designed to study the flux of coastal carbon from the near-shore to the open ocean, which is postulated to be an important term in the ocean carbon budgets. The OM&L study is designed to study the cascade of optical variability from very small scales (cm) to tens of kilometers, and is thus highly relevant to understanding effects of intra-pixel variability when merging data with varying IFOV's. The present Chesapeake Bay LMER study focuses on relationships of secondary and higher level production in an estuarine system, and was preceded by a study of nutrient transformations in the estuary-water shed system. The investigation can provide a useful framework for verification of adjacent bright target effects on atmospheric correction and in-water properties. The CalCOFI program in the Southern California Bight has produced an invaluable time series of biological

observations relevant to the validation and use of ocean color data. This has been augmented with improved optical measurements by NASA, which should continue perhaps with additional augmentation in the areas of new production estimates.

New technology exploitation

Applications of new technologies such as data acquisition systems and automated in situ are widespread in all of the missions and the previous calibration and validation sections. The following two SIMBIOS components are especially representative.

Instrumentation for opportunistic sampling: Technological advances in marine optical instrumentation, data processing, storage, and relay now enable serious consideration of opportunistic sampling of basic bio-optical properties. These activities have the potential for providing a variety of time series observations, but with somewhat lower accuracy than those obtained on focused research cruises. Of particular interest are automated, self-contained towed systems that require a minimum amount of preparation and care. These systems can collect continuous data while the ship is underway and can “yo-yo” vertically to obtain profiles of bio-optical parameters. These measurements include chlorophyll fluorescence, upwelling and downwelling irradiance, optical absorbance and scattering. Ships of opportunity include research support vessels servicing remote moorings and field studies, fisheries vessels (which would provide coverage of important fisheries), the operational fleet, and scheduled transoceanic ships. Operational assets (NOAA, Navy) are increasingly available for dual-use. One example is the recent collaboration between the Naval Oceanographic Office (NAVO) and NASA/SSC for collection of bio-optical data. Because research vessels provide very limited coverage and also because of the available technology, ships of opportunity should be exploited. Opportunities to develop and implement programs for opportunistic and/or piggyback sampling should be included in the SIMBIOS program. Procedures to ease restrictions on data collection in EEZ’s should also be explored. Modest expenditures of funds in this area are likely to provide a large return.

Bio-optical moorings: Extended time series of observations in remote regions, and which are also cost-effective in the coastal zone, can now be made effectively from instrumented buoys which employ two-way communication with laboratories ashore. While SeaWiFS and MODIS have concentrated on precision and reliability at a single site for vicarious calibration purposes, the need is clear to extend basic capability much more broadly for spatial and temporal validation purposes. Feasibility studies for providing instrumentation and support to augment NOAA’s data buoy system are underway. Additional interest exists in augmentation of the TAO moorings in equatorial Pacific and elsewhere. It is recommended that opportunities to augment existing physical moorings with bio-optical sensors be discussed in the NRA with the intent to select two augmentation projects.

DATA MERGING

Level-3 Product Types

A global Level-3 data type, that will serve as the basic platform from which long-term trends may be observed, should be established. The data set should initially be identical to the SeaWiFS level-3 binned product, which is well defined and which will be compatible with OCTS level-3 data. The temporal and spatial resolution of the data set supports global studies: 9-km by 9-km in an equal area arrangement in space; daily, 8-day, monthly, and annual time scales. The stored variables should

also be the same: sum, sum of squares, n, and a weight. These will enable statistical measures of the user's choice to be easily calculated, and supports several representations of central tendency: arithmetic mean, geometric mean, median, etc. Greater spatial resolution can be considered once newer technology sensors like MODIS and MERIS are launched. SeaWiFS and OCTS data could then be recommended for re-processing to maintain continuity.

It is also recommended that a global coastal data set at higher spatial resolution be established. In these coastal areas, human impacts are being felt today and will become more critical in the coming decades as a result of human population growth and its concentration in coastal areas. Ocean color data will be a tool for fisheries managers, coastal geologists and hydrologists, and for state and local agencies that monitor water quality. Although required spatial scales for many coastal processes are far too fine for existing missions, the highest resolution grid possible should be selected. This is 1-km for SeaWiFS and OCTS, as well as most of the ocean color bands for MODIS, MERIS and GLI. The domain is to be decided: perhaps to the 200-m isobath worldwide or the 200-mile limit. For global products, the present suite of temporal scales defined for the SeaWiFS level-3 products are sufficient.

One of the more exciting aspects of combining data from multiple missions is the prospect of producing new data products or resolutions. For example, level-3 products at higher frequency than daily may be possible, although perhaps only at higher latitudes where there is substantial orbital overlap. Three-hour, 6-hour, or 12-hour data sets would greatly enhance our ability to detect diel changes in phytoplankton abundance, and perhaps show us how our noon and 10:30 crossing times relate to the average daily biomass. It is not certain that a useful data product can be created, especially given clouds and low solar zenith angles, but a study to investigate the possibility is recommended.

Products

The ocean color products most viable as candidates are those that are (1) routinely processed, and (2) represent bio-optical and geophysical variables of wide interest. Initially,

- CZCS-pigment (derived from CZCS bands)
- Chlorophyll-a
- Attenuation coefficient
- Aerosol optical thickness

would be the parameters used for creating time series. These are all products that are planned for production by SeaWiFS and OCTS, as well as successive sensors. Other products are being proposed for MODIS, and possibly others for MERIS and GLI, that should be considered for new time series when they begin to be produced. Considering only the MODIS products, these are:

- Chlorophyll fluorescence
- Colored dissolved organic matter
- Coccolith concentration
- Primary production

Certainly, primary production and coccolith concentration will become standard products for SeaWiFS and OCTS once the algorithms are defined.

It is noteworthy that the most fundamental ocean color variable, water-leaving radiance, is not recommended for a merged data set. Although the radiances are critical for determining differences in many of the recommended derived products, such as pigment, attenuation coefficient, etc., they are not as useful as products. A long-term time series of water-leaving radiances is less important than the bio-optical products derived from them. While they will be necessary if problems are found, or differences occur, in the other bio-optical products, they are best used in level-2 form from the originating sensor. These data will presumably be stored at the data centers responsible for the individual missions. Similar reasoning applies to other aerosol related quantities such as the aerosol radiances in the near-infrared, which are by-products of aerosol characterization.

Data Quality Requirements

Before any two data sets can be merged to produce a useful, and consistent, time series, the quality of the data must be assured. This is not a trivial task. Previous attempts to merge data, such as the Advanced Very High Resolution Radiometer (AVHRR) and Active Cavity Radiometer Irradiance Monitor (ACRIM), have shown the inherent difficulties, and these used a series of similar sensors. The diversity of the ocean color sensors proposed by international agencies suggests that the creation of a long-term time series will be a difficult task, perhaps requiring substantial computation and personnel resources.

Potential sources of error can be identified a priori with knowledge of the fundamental steps required to produce mapped, binned, level-3 ocean color data products. Their location in the processing flow can also be identified, so that if re-processing is required, as was done in the AVHRR Pathfinder Project, the potential burden may be assessed.

navigation	(Level 1; Level 2)
calibration	(Level 2)
atmospheric correction	(Level 2)
bio-optical algorithms	(Level 2)
space and time binning	(Level 3)

(Processing level indicates the final product level resulting from the processing considered. For example, atmospheric correction uses level-1 data, and produces level-2 data; therefore it is considered a Level-2 procedure). At Level-3, inconsistencies among data sets in IFOV and sampling frequency or repeat time are inconsequential as long as they are within the proposed level-3 product resolutions. This is true for all the proposed sensors considered in the foreseeable future.

If significant differences are found among any of the proposed data sets, then it must first be ascertained from where those differences occur. The above table shows generally where these differences can occur in the processing flow. Before data sets can be merged, it must be established that differences in any of the above sources of error are insignificant. Significance can be defined in terms of relative errors, thus providing us a quantitative measure of data quality requirements.

This relative error assessment proceeds as follows:

navigation: the error in knowledge of geolocation of each data set must be within the spatial resolution of the level-3 grid

calibration and atmospheric correction: the difference in the level-2 water-leaving radiance product between any two data sets must be less than the established minimum atmospheric correction algorithm error. A 2 sigma confidence level is sufficient.

bio-optical algorithms: the difference in the level-2 candidate product (CZCS-pigment, chlorophyll-a, etc.) between any two data sets must be less than the established minimum bio-optical algorithm error. Again a 2 sigma confidence level is sufficient.

space and time binning: the level-3 space and time resolutions must be less than or equal to the proposed merged product level-3 grid and time specifications, and must consist of the specified fields.

If any data set does not meet any of these requirements, there are three choices:

- (1) discard the data set
- (2) reprocess the data set from the processing level preceding the problem.
- (3) apply a correction method

At this time, solutions cannot be determined since differences and sources of error are not known. However, the most expensive solution, reprocessing, must be seriously considered, and data system requirements must accommodate this possibly. In the cases of SeaWiFS, MODIS and MISR, these reprocessings will be handled by the SeaWiFS and EOS Projects which are scoped to accommodate periodic reprocessing. In the cases of the other missions, this program may have to assist with the reprocessing. Overall estimates to assist the data system design are provided later in this document.

Determination of Data Set Compatibility

As described above, the data quality requirements for the merged data set, and the potential sources of error have been defined. The issue is how to evaluate data set compatibility, or, in other words, how differences in data sets will be determined. To this end, the creation of a test data set (or Diagnostic Data Set) that will contain the information necessary for determining compatibility is recommended. This information (calibration constants, sensor gains, raw digital counts, algorithm parameters, etc.) is readily available and accessible during the initial processing of the data and should be used for merging, but is generally discarded in the Level-3 data product. Thus, at the time that the initial data are processed, a Diagnostic Data Set should be created by each sensor project.

The Diagnostic Data Set will contain data and ancillary information for individual pixels located at a fixed spatial grid, to enable detailed analysis of algorithm errors, sensor performance, etc. for each of the data sets. The grid-point spacing will be relatively large in open ocean areas but will get finer near shore. Considerations for the grid include:

- (1) more points in coastal areas
- (2) more points in known dynamical ocean areas (one can assess the statistical variance of the oceans using CZCS data to select these points)
- (3) heavy sampling in known international and national validation areas
- (4) sufficient open ocean points to enable vicarious calibration/algorithm comparisons
- (5) total data set size small enough to be manageable, and to not produce a burden on the individual projects that must provide these points.

The parameters that must be included in each point or pixel in the set are:

- (1) attitude (roll, pitch, yaw)
- (2) orbital position and time
- (3) geolocation (latitude and longitude with accuracy to the size of the sensor's pixel)
- (4) pixel number in the scan and/or scan angle from nadir
- (5) raw counts for each band
- (6) computed level-2 water-leaving radiances for each band
- (7) computed level-2 CZCS-pigment, chlorophyll-a, aerosol optical thickness, attenuation coefficient (if any of these are not produced routinely by an ocean color project in charge a the data set, the data set will not be used in the merged data set)

Daily values of each must be provided, and it is recognized that multiples of high latitude pixels will be produced. There is no time requirement for delivery. Completeness of the set is more important than timeliness, so every effort should be made to lessen the impact on the processing systems. Off-line access to calibration equations, coefficients, sensor count-to-radiance equations, and fundamentals of the operation of the spacecraft (especially attitude control systems and sensors) are also required. These can be in the form of hard copy sensor manuals.

In order to keep the data management process under control, the Diagnostic Data Set should contain about 30,000 points globally. Given the requirements of contents stated above, and assuming an average of 11 bands per mission, this works out to about 5 MB per day per mission. Thus, the diagnostic data volume will be manageable, not overly burdensome, and extremely valuable in later years to assess the performance of various sensors over a 20 year time period.

For the global coastal 1-km data set, navigation is a more important driver in determining data set compatibility. The Diagnostic Data Set cannot provide navigational accuracy assessment, since it is so sparsely sampled. Thus, small, representative, but not sub-sampled portions of the data sets to evaluate navigation accuracy will be required. It is also suggested that perhaps a full day of global data each week for the first 4 months of each mission will be needed. The global navigation accuracy assessment techniques developed for the SeaStar mission to ensure the compatibility of the data sets can be applied. These methods currently require only 2 bands: 412 and 670 nm. Level-1 data is required.

International Agreement Requirements

Since the goal of producing a long-term time series of ocean color data requires data from various sensors, many of which are planned by the international community, agreements between NASA HQ and the respective mission management agencies will be necessary. The availability of data must be guaranteed, methods for distribution agreed upon, and data formats must be established by consensus.

Detailed information on sensor configuration specifications, on-board attitude control systems, telemetry data, signal-to-noise ratios, counts-to-radiance conversion methods, and details on the on-board calibration methods, as well as calibration equations are required. These can be one-time-only deliveries of hard copy sensor manuals, that need only be updated when changes occur.

Data System Requirements

Data system requirements follow from the recommendations listed below. The establishment and maintenance of three distinct data sets are required:

- (1) Global 9-km binned (Level-3) data set, at daily, 8-day, monthly time steps, consisting of the following products:

- CZCS-pigment
- Chlorophyll-a
- Attenuation coefficient
- Aerosol optical thickness at 865 nm

With launch of MODIS in 1998, the following products will be added:

- Chlorophyll fluorescence
- Colored dissolved organic matter
- Coccolith concentration
- Primary production

The data set will use data from SeaWiFS and OCTS beginning in 1996, and MODIS beginning in 1998, followed by data from MERIS and GLI beginning in 1999, and continue for a 20-year period.

- (2) Global coastal 1-km binned (level-3) data set, at the same time resolution as the global set, consisting of the same products, from the same sensors. This will require level-2 data since level-3 data are not routinely processed at 1-km resolution for SeaWiFS and OCTS
- (3) Diagnostic data set of 30,000 points selected on a non-uniform grid to encompass open oceans, coasts, and especially validation sites, from each sensor. The data set should be delivered routinely, consisting of pixel values at daily intervals. The Diagnostic data set values should consist of:

- attitude (roll, pitch, yaw)
- orbital position and time
- geolocation (latitude and longitude with accuracy to the size of the sensor's pixel)
- pixel number in the scan and/or scan angle from nadir
- raw counts for each band
- computed level-2 water-leaving radiances for each band
- computed level-2 CZCS-pigment, chlorophyll-a, aerosol optical thickness, attenuation coefficient

The size is approximately 5 MB each.

- (4) Navigation assessment data set, consisting of one full day of global level-1 data at 2 selected bands (probably 412 and 670 nm) each week for 4 months. Level-1 from each sensor, but only during this 4-month period unless there is reason to suspect a major change in attitude control or knowledge.

Occasional reprocessing entire data sets from level-1 for each sensor will be necessary if not undertaken by the individual projects.

Science Team

A small, executive science team on data merging issues should be formed. The responsibilities of this team would be:

- (1) determine the compatibility of data sets based on information provided by the recommendations given here
- (2) determine the exact location of the grid points in the Diagnostic Data Set
- (3) provide recommendations on actions resulting from incompatibilities in data sets (reprocessing, elimination, or correction)
- (4) determine when to add new products or delete old ones, and whether the grid sizes should be changed
- (5) oversee overall performance and quality of the merged data sets

Resource Requirements

Most of the required resources for merging data sets involve data acquisition, processing, and storage, and thus are included separately in the data system budget. There are some analysis responsibilities involved in assuring compatibility of data sets, and identification of errors. Given the small data samples required and recommended for this purpose, a single full-time person with at least Master's Level physical or biological sciences background should be sufficient.

DATA PROCESSING

The primary goal of the data system component of this program is to produce a long-term set of biological and parameters derived from ocean color satellite observations that will be acquired over the next five years. To accomplish this task, a number of specific objectives need to be addressed, including those detailed in the other sections of this plan. However, to accomplish those objectives requires a significant degree of system-related support and capability. It is that capability that is the focus of this section. While the following discussion is somewhat general in nature, two assumptions are applied in scoping the system as costed in the budget section, (1) in addition to the product evaluation and merger functions, the system must be capable of handling a satellite data stream from level-0 through level-3 and (2) the archival and distribution of the products generated by the SIMBIOS Project will be handled by the DAAC. The first requires that processing software, pre-launch sensor calibration and characterization data and documentation on each be readily available for all missions under consideration. These needs must be addressed at the international level. The SeaWiFS Project has established a precedent for such exchange as all operational processing system code is available as is the SeaDAS (SeaWiFS Data Analysis System) code. SeaDAS is a simplified version of the operational system designed for use by individual researchers.

Many elements of the program described in this plan currently exist as individual activities at the national as well as international level. The major challenge of this activity, therefore, will be to bring these functions together so that all elements can function in a seamless and mutually beneficial way. Where neither the capability exists, nor where it can be readily integrated, these functions will need to be developed. The three major functional elements of this activity consist of Data, Processing and Information. The primary objectives for each of these elements are:

Data: To ensure that the specific data sets required by each element in the program are available in a timely and readily accessible manner.

Processing: To maximize the reuse of existing software and methodologies to the greatest extent possible and to make certain that any newly-developed software is as flexible as possible.

Information Management: To develop an implementation strategy that maximizes the information content of the data products and makes that information available to as wide an audience in as simple a manner as possible.

To meet these objectives, an implementation strategy must be developed that is based upon a specific set of assumptions, requirements and capabilities. In addition, specific recommendations arising from the three-day international meeting to help formulate this plan have been included and are listed under their appropriate sections.

Data

Identify all data sources, volumes and access requirements required by this program. Wherever possible, use existing agreements and data transfer mechanisms to acquire those data sets that need to reside routinely within this program as contrasted with those that can be obtained on an as needed basis. For example, the JGOFS distributed data management system along with the online repositories of the Hawaii and Bermuda Time Series activities are good examples of data sets that can be readily accessed on an as needed basis. Historical phytoplankton pigment data sets like those held in the SeaWiFS Project's SeaBASS archive is an example of the types of data sets that required consolidation and significant work before they could be effectively used.

Access to satellite ocean color data sets other than SeaWiFS is one of the key elements this program. However, the processing level required and the degree of reprocessing needed to produce the products defined by the data merger element will depend primarily upon the sources of errors and uncertainties identified in the operational products produced by the various ocean color projects. The sources of errors and the proposed strategy for dealing with them is described in the Data Merging section of this document. Although the coordination and responsibility for the acquisition of the data sets, in particular the calibration and validation data needs as defined below, are the responsibilities of the individual elements, the overall management, access and manipulation should be handled within the data system component. If the goal is to provide seamless and simple access to all the data sets under consideration by this program, then having a unified data management system is a key requirement. To facilitate the exchange of data, a consistent set of metadata should be provided for each data set that will be used in this program. For the non-satellite derived observations, the metadata description outlined in Hooker et al. (1994) is a very good starting point.

As for satellite data, the SeaWiFS example is also a good strawman, particularly since close collaboration with the CEOS group early on in the format definition phase has made the exchange of SeaWiFS data between these groups less burdensome. However, specific data format translators (for instance HDF to CEOS) will most likely still need to be developed for the software developed by one group to be used on the data collected by another.

Specific Data Set Requirements

Calibration Element:

- (1) Round-robin data sets
50 MByte per experiment. Approximately 2 experiments per year
- (2) Pre-launch and on-orbit calibration data
volume TBD
- (3) MOBY data
1 MByte per day
- (4) Satellite data
Highest Resolution available for all vicarious calibration targets, 1 scene per target every 2 days, approximately 30 seconds SeaWiFS LAC-type data (4 MBytes)
- (5) Initialization Activity data sets
approximately 50 Mbytes per experiment day
- (6) Cloud top reflectances and cloud top height measurements
volume TBD
- (7) Bio-optical data sets
volume TBD

Validation Element:

- (1) Validation experiment data sets (oligotrophic, high aerosol, high latitude, turbid, bright target)
approximately 50 MBytes per experiment day
- (2) Aerosol-related measurements:
 - (a) aerosol optical properties (optical thickness, sky radiance)
 - (b) aerosol vertical profiles
- (3) Surface structure measurements:
 - (a) whitecap spectral reflectance
 - (b) wind speed and direction

Data Merger Element:

- (1) Diagnostic data set for each satellite mission
approximately 5 Mbyte per day per sensor
- (2) Navigation assessment data set
1 day global level-1 data at 2 bands each week for 4 months
- (3) Global coastal 1 km binned data set
global coastal level-2 data for all sensors
- (4) Global 9km binned (Level-3) data set
merged product incorporating new sensors and products

Processing

The processing requirements for this activity will vary with time as new missions come online and as new products and strategies are developed. Therefore, the system must not only be flexible, but must also be easily scaled up and down as the demands on the system change. It is proposed that the SeaWiFS Data Processing System be used as the model for the processing component of this program since it has been developed specifically with those criteria in mind. The majority of the required system programming involves the infrastructure necessary to move large amounts of data through the system in as simple and automated a manner as possible. The SeaWiFS Data Processing

System has shown itself to be quite capable of handling this requirement. The mission-specific components of the processing system will for the most part be able to be obtained from the agencies responsible for the mission itself. For instance, it is assumed that standard OCTS processing algorithms will be available for incorporation into the above-mentioned system with the data management aspects being handled by the components from SeaWiFS. However, a number of mission-specific programs will need to be developed to make this incorporation possible. As mentioned above, format translators and metadata extraction utilities are two examples. While much of the software and expertise to carry out this activity currently resides within the SeaWiFS Project, those resources will be fully committed once SeaWiFS is launched. Therefore, this activity should be developed in parallel with its own set of computational resources and programmers.

The size and scope of the processing system will be refined during the initial phase of this program, but initial estimates based upon past experience and currently available technologies can be made. At the onset in the CY 1996-1997 time frame, a system capable of handling a subset of the SeaWiFS and OCTS data flow plus all the currently available and scheduled in situ and calibration data sets related to those mission will be needed. To size the system, it is necessary to have a realistic estimate of the number, scope and volume of the data sets that the system must accommodate. The specific data sets identified by each element in this program are listed below. Where possible, estimates of their volumes have been given.

Information Management

With the revolution in information access that has accompanied the development of the World Wide Web (WWW), the concept of a distributed information system with nearly immediate access is very close to becoming the standard by which all systems will be judged. In addition to ready access to data and information, this form of information system offers a degree of platform independence that people have been advocating for years. It is proposed that whatever system is eventually developed to carry out the requirements of this program, a concurrent development of the WWW interface be undertaken.

INTERAGENCY AND INTERNATIONAL COORDINATION

The project, by its very nature, will require the participation of space agencies that operate ocean color satellites (CNES, ESA, NASA, NASDA, etc.), as well as governmental bodies and academic institutions worldwide to process and analyze the satellite data, develop and refine retrieval algorithms, and evaluate the derived products. The various activities will be coordinated by an International Ocean Color Working Group (IOCWG), the Committee on Earth Observing Satellites (CEOS), a United States (U.S.) Interagency Coordination Group (ICG) and an Ocean Biogeochemistry Science Advisory Panel (OBSAP). Figure 8 provides an organization structure and the responsibilities of each group are briefly discussed below in this section and in the following section on implementation. The exact composition and charter of each group will need to be defined, but it is sufficient at this time to merely provide a rough sketch of the organizational requirements. All groups provide advice to the NASA Mission to Planet Earth Program (MTPE) which then directs the SIMBIOS Project Office (SPO). These bodies will gather scientific advice (necessary to ensure that user requirements are properly represented and that the remote sensing data sets will adequately support scientific activities), promote joint development and consensus on bio-optical and atmospheric correction algorithms, seek national commitments on data exchange and international agree-

ments on data formats and measurement protocols, and review the data management and implementation plans. Each body will have distinct, yet complementary roles and functions.

The IOCWG will work to achieve consensus on the following:

- (1) the ocean color products that satisfy the needs of the scientific communities, which products should be created (e.g., monthly, 9 km resolution pigment concentration over the global oceans),
- (2) the requirements for the products (parameters, resolutions, formats, etc.),
- (3) the algorithms to derive the products, develop plans to evaluate the products, and
- (4) measurement protocols to ensure quality of the validation datasets.

Additionally, the IOCWG will serve as the following:

- (1) a group which can recommend and endorse data and software exchange requirements and agreements between the various missions and space agencies and
- (2) a group that can assist in the coordination of field programs.

Workshops may be organized and ad hoc committees or subgroups may be formed to address specific issues. The IOCWG will be composed of experts in ocean color remote sensing and potential users of the products (e.g., physicists, biogeochemists, and resource managers), and will include liaisons to members of critical international experiments and measuring programs, and the project scientists of the various satellite missions. The liaisons will help ensure that scientific needs of IGBP core projects, namely JGOFS, LOICZ, GOEYS, of GLOBEC, and of national projects are met (the liaisons may also be members of those projects). The Working Group may be an extension of the Joint U.S./Japanese Working Group on Ocean Color, which has been successful in coordinating OCTS and SeaWiFS activities.

The recommendations of the International Working Group on Ocean Color will be presented to the Committee on Earth Observing Satellites (CEOS) for comment. Specifically, the CEOS Working Group on Data (WGD) will review product specifications related to format, catalog system support, networking requirements, and data management and distribution strategies. The CEOS Working Group on sensor Calibration and geophysical Validation (WGCV) will review techniques and standards for calibration of the ocean color sensors and validation of the geophysical parameters and promote standardization of methodologies. The Working Groups will provide guidance and support for the appropriate agreements and Memoranda Of Understanding (MOU) on (1) the exchange and distribution of prelaunch instrument calibration and characterization data, post-launch calibration data and in situ data, (2) the coordination of joint field programs for validating the sensors, testing oceanic and atmospheric algorithms and (3) the development of new applications from CEOS members (i.e., space agencies) and their affiliates (i.e., IGBP, ICSU, IOC, GOOS).

Some international agreements and MOU's already exist for access by the U.S. to specific foreign ocean color datasets (OCTS, POLDER) and for access by foreign countries to U.S. ocean color datasets (CZCS, SeaWiFS, MODIS). An agreement between Japan and the U.S. is being finalized for broader cooperation in ocean color remote sensing, and some agreements and MOU's are being negotiated (access to GLI, MERIS, and MOS data). These agreements and MOU's are described in more detail in Appendix B.

Most of the work supported by the U.S. program will be funded through a NASA Research Announcement (NRA) as grants. The SPO will contract certain tasks out which have definite hardware and software deliverables. These are identified in the budget section. In the U.S., a standing ICG on ocean color will identify contributions of the various agencies and agree on collaborative efforts. The ICG, composed of representatives (program managers) of NASA, NOAA, DOE, NSF, USGS, the Navy, ONR and EPA, will provide a forum to communicate and coordinate activities of the member agencies, and enhance the complementary aspects of their ocean color (and related) programs. The OBSAP will provide guidance on the objectives and implementation of the NASA ocean biogeochemistry program and will help define the products that the SIMBIOS Project should generate. This will help ensure that the SIMBIOS Project objectives are aligned with the U. S. science community requirements. Though the realization of the project, from definition to execution, requires successive steps, consultation between each of these groups and other participating organizations will occur continuously during all phases of the project. Points-of-contact will be designated, and procedures for reporting and disseminating information will be established. The SIMBIOS Project will answer directly to the NASA MTPE program who will schedule periodic briefings to the IOCWG, the ICG and the OBSAP.

Finally, the SIMBIOS Project will establish working groups on (1) calibration, (2) bio-optical algorithms, measurement protocols and data merger algorithms, (3) atmospheric correction algorithms (4) primary productivity and (5) data processing. The first four are continuations of SeaWiFS Science Working Group subgroups which will officially terminate in 1996 at the end of the SeaWiFS NRA program. The fourth group will be added to ensure that issues such as processing software exchange, formats and networking are addressed. Participation in the groups will be international and the U.S. participants will include those funded by NASA, either through the R&A program, the NRA or instrument teams.

IMPLEMENTATION PLAN

Scope and Organization

The implementation plan describes how and when activities will be executed and what the SIMBIOS Project organization structure should be. Program milestones and level of effort are determined primarily by the launch schedules of the primary missions (SeaWiFS, OCTS/POLDER, MODIS/MISR, MERIS and GLI), by the calibration and validation activities being conducted by the individual missions, and by the funding profile for this project (the current profile was defined based on a satellite mission procurement, i.e. a large first year allocation with relatively small and level funding thereafter).

The management of the program needs to be clearly defined. Given the scope and operational nature of the program, a formal management structure that ensures sound guidance, accountability and execution will be necessary. While it is ultimately the decision of GSFC and NASA Headquarters management to determine how the program will be directed, a strawman structure with key responsibilities is provided in Figure 8. It is assumed that the program will be handled out of GSFC. The proposed structure of the SPO has elements for calibration, validation, data merger, data processing and international/interagency coordination. The Project would be supported by five working groups as shown in Figure 8 and would have the authority to call these groups together on a regular basis. The element managers at GSFC would be matrixed with the SPO. The SPO provides administrative

support, handles the contracts identified in the budget and oversees any data processing systems supported by the program. As shown in the budget, much of the work will be funded through an NRA handled out of NASA HQ.

The SPO is modeled after the SeaWiFS Project and consists of an office manager, element managers and support staff. An estimate of the total staffing of the SPO, including staffing for all of the elements, is about 21 man years/year and is based on the experience of the SeaWiFS Project. The SPO will have the responsibility of handling the routine data processing requirements, e.g., ingest and level-2 & -3 processing of foreign mission data and level-3 merging of the multisensor data sets that meet the data merging selection criteria. The SPO would also be responsible for expanding and maintaining the SeaBASS archive and would undertake in situ data analyses of the contributed data sets to derived products, e.g. reflectance, remote sensing reflectance, water-leaving radiance, using standard quality control and processing procedures. The current in situ data archive activity within the SeaWiFS Project only undertakes the documentation and archive ingest of contributed data sets with no effect to quality control or process the data to more useful products for algorithm development and validation.

Activity Schedule

Figure 9 provides a milestone chart of the U.S. participation in the overall international program. The activities are separated into the project element categories and are color coded by primary funding source to avoid any suggestion of duplication of effort. The "Other Project" includes SeaWiFS, foreign missions and field programs supported by NASA and other agencies. In most cases, SIMBIOS will augment activities primarily funded by other projects, e.g., JGOFS Southern Ocean program. The chart also shows that every six months, the project will determine if new tasks not covered by existing NRA grants or contracts have been identified. If so, solicitations for proposals will be released. A CZCS reprocessing will be initiated at the earliest opportunity.

BUDGET JUSTIFICATION

In the previous sections, the activities under each component of the SIMBIOS program have been described. Table 4 provides a breakdown of the annual costs for the various activities which are partitioned as SIMBIOS Project Office, calibration, validation and data merger. As mentioned earlier, the budget does not cover costs for product archival and distribution as it is assumed that the DAAC will handle these responsibilities in a manner analogous to SeaWiFS. The justifications for the funds listed in Table 4 are provided below.

The SIMBIOS Project Office

For the purposed of cost estimation, it is assumed that the SPO will be located on-site at GSFC. The SPO includes administrative support, support for project documentation, the data processing system, the support staff for each of the elements and GSFC on-site manpower costs (assumes a total of 21 man years/year). If the SPO is located off-site, the on-site manpower costs would reduced to the cost of renting space. Having the SPO located next to the SeaWiFS Project would have obvious benefits. The administrative support includes an administrative assistant because civil service staff will not be available. It also includes a technical editor to ensure that the outputs from the project are documented in a technical memorandum series such as produced by the SeaWiFS Project. Other items

are office equipment (microcomputers, software, networking costs, etc.) and meeting support. It is expected that the project will support travel for working group meetings.

As stated in the data processing section, the system is scoped to handle routine processing of level-0 to level-3 data from a sensor such as OCTS or MERIS as well as perform the data merger tasks. This requirement defines the data processing budget profile with major purchases in the first year (primary processing system, workstations, disk storage, tape backup system, commercial software licenses, high capacity network support, etc.) and upgrades in the third year in advance of missions are scheduled to be launched in the fourth and fifth years. Given the data processing requirements, a group of seven programmers and system managers will be need to handle the data system responsibilities. The general tasks that this group will address include:

- (1) Data base programming and management,
- (2) Scientific programming and algorithm integration
- (3) Data formats and metadata extraction applications
- (4) System management support and programming
- (5) Data processing applications and utilities programming
- (6) Information systems and network applications

The data system budget also includes roughly \$250K/yr for system maintenance. These estimates are based on experience in managing the SeaWiFS data processing system.

The SPO budget also includes staff to support the calibration (an analyst and a post-doc), validation (2 analysts and a post-doc) and data merger (an analyst and a post-doc) elements. The tasks that these individuals will assist with include the following:

- (1) assist in the collection, processing, archival and documentation of the calibration (including round robin, pre- and post-launch sensor calibration) and the bio-optical data sets,
- (2) accompany the SXR to calibration laboratories for periodic checking of their sources,
- (3) assist in data acquisition during major field studies, e.g. the (PML/AMT),
- (4) assist in product validation and quality control assessment, and
- (5) assist in the development, evaluation and implementation of product merger schemes and algorithms.

Experience in preparing the SeaWiFS has shown that all of these activities are crucial and very time consuming. For example, the definition, coding and documentation of the initial set of SeaWiFS level-3 products (Campbell, et al., 1995; McClain et al., 1995; Podesta, 1995) are just now being completed and three separate proposals for future modifications to the suite of level-3 products have been recently submitted to the SeaWiFS Project for evaluation.

Calibration

Calibration Scale Traceability

The term “scale traceability” means that all satellite and in situ instruments are linked to a common standard. Three activities are identified to help ensure that this goal is accomplished, calibration round robins, field stability monitor support and community in situ instrument calibration support.

The round robins would be hosted by NIST and augment support from the EOS Project Science Office. The support to NIST covers two calibration round robins per year, one round robin focused on laboratory methods and source comparisons (spheres and plaques) and a second specialty round robin. Specialty round robins would focus on such things as solar based calibrations (Biggar et al., 1995) and visits to foreign laboratories e.g. Carol Johnson's recent visit to NEC in Japan to characterize the sphere used for calibrating OCTS. The support would also include maintenance of the SeaWiFS transfer radiometer (SXR) and periodic recertification of the stability monitors.

The stability monitors are low-cost (< \$10K) sources which will be taken to the field for routinely checking the calibration stability of in situ radiometers. These are particularly necessary in cases where the radiometers are only recalibrated after many deployments (e.g. PML/AMT cruises and Bermuda Atlantic Time Series cruises). The stability monitor provides a way of checking the relative calibration of each instrument band to see if changes are monotonic or abrupt so that the a time dependent calibration can be applied once the instrument is recalibrated in the laboratory. Under SeaWiFS Project support, NIST has developed a design (no affordable commercial designs were available). The SPO would purchase a number of these, depending on the final price, and loan them to investigators. NIST will build the prototype and a competitive RFP will be released for a commercial source to build the others following the NIST design. Funds after the first year would be for maintenance and replacement of units.

Community calibration support would provide for calibration services to the community. The SeaWiFS Project contracted for such services in the past to help ensure calibration standardization and traceability. The marine optics community has voiced a desire to see this service expanded. Otherwise, investigators paid directly out of their research budgets and can be inclined to postpone having instruments recalibrated when budgets are tight. This approach offers reduction in the cost per calibration because calibrations are purchased in bulk numbers. The budget covers the estimated cost of a full time calibration technician and equipment upgrades (lamps, plaques, power supplies, etc.) required to meet NIST standards. The service would be included in the NRA solicitation.

Special studies

Given that each instrument listed in Table 1 has a unique design (except for MODIS AM and PM), each will require special attention. Special studies include such activities as

- (1) the documentation of foreign mission prelaunch sensor calibration and characterization results (in some cases, translation to English of existing documents may be necessary),
- (2) experiments designed to quantify and correct stray light and out-of-band radiance effects after launch,
- (3) the development of strategies for combining the post-launch calibration results from various techniques, and
- (4) the development new and innovative approaches for post-launch calibration.

The budget provides support for at least 2 special studies per year.

High latitude calibration and validation verification

Because high latitudes present unique problems for both sensor calibration and algorithm (bio-optical and atmospheric correction) performance, field programs explicitly designed for high latitude (north and south) are included in the plan. Most existing observation programs which provide

comprehensive in-water and atmospheric measurements (Figures 5-7) are located at low and middle latitudes with few opportunities to augment ongoing field studies. In the southern hemisphere, the LTER and JGOFS Southern Ocean programs will be approached regarding cooperative efforts, but, in the case of JGOFS, berth space and wire time are fully utilized requiring separate bio-optical cruises. Therefore, the SIMBIOS program will fully support one comprehensive study per year at high latitudes. The budget includes ship time expenses.

High altitude vicarious calibration

High altitude measurements of well-characterized sites largely remove aerosols from the radiation budget (Figure 4) and offer many advantages over other methods for post-launch sensor calibration (Table 2). Although Phil Slater is funded through the SeaWiFS NRA (terminates in 1996) and MODIS instrument teams to conduct such calibrations for those sensors, no U.S. investigator is supported to conduct vicarious calibration studies for any of the foreign sensors. Given the known stray light characteristics of SeaWiFS and MODIS and assuming that other instruments have similar problems, selection and characterization of an appropriate site may require considerable effort and logistical support, especially if deployment to foreign sites is required. The budget supports two observation campaigns per year which is considered the bare minimum for developing a calibration time series.

Common atmospheric correction algorithm implementation

For the purposes of vicarious calibration and routine data processing, a common atmospheric correction scheme should be used. Otherwise, differentiation of sensor effects and atmospheric correction biases cannot be easily achieved. Therefore, a budget line to support the implementation of a common algorithm to at least the suite of global missions (Figure 1) is included. The work would also include the comparison of the calibration corrections obtained by using the operational algorithms of each ocean color satellite project. This would be supported through a contract to the SPO rather than a grant.

Validation

Augmentations to sun photometer network

Funds are identified to augment the island sun photometer with instruments of the CIMEL type for validation of atmospheric correction parameters. Estimates are for 4 instruments (Lanai, La Jolla, Wallops and ship deployed) at \$22K/instrument, with 10% for calibration, and the remainder for calibration, installation, servicing, and analysis. The infrastructure is already built and working fine under the direction of Brent Holben.

Field studies

Productivity time series: Funds are requested for beginning a time series of productivity in productive waters and preferably at higher latitudes, in conjunction with a TBD coastal ocean program. This is envisioned as monthly to bimonthly sampling of input parameters (profiles of bio-optical properties) and ¹⁴C techniques. The purpose is to provide a consistent set of data to test seasonal to annual productivity algorithms as well as daily or short term. Since all productivity algorithms are empirical to a certain extent, such a time series will be invaluable in confirming whether changes in productivity derived from sat is real, or due to changes in algorithm parameters. The funds would cover an investigator, technician, supplies, and analysis. Data would not be proprietary, and would be included in the SIMBIOS data base in a quarterly basis.

Augmentation of U.S. studies: Funds to support studies in association with the Oceans Margin Program (DOE), Ocean Mixing and Light Program (ONR), the Chesapeake Bay LMER program (NOAA) and the CalCOFI (NOAA/NMFS) are also requested. This will cover activities such as enhanced optical measurements, travel support and data analysis.

PML/AMT cruises: Funds for the PML/AMT program are required for 3 investigators to participate in each semi-annual PML/AMT transect. The budget includes costs for travel, shipping, some dedicated capital equipment (optical profiler, productivity apparatus, aerosol optical depth instrumentation) and timely submission of data reports. A decision regarding whether gear is returned from the Falklands in October and sent back in March, or stored over the austral summer must be made. Additional station time may be included if PML's proposal is rejected, but at the expense of other components.

Initialization cruises (augmentation): Funds are requested for ship time following the launches of OCTS, MERIS and GLI to collect data required for initialization of algorithms for those sensors, using the same techniques as for SeaWiFS and MODIS. The field observations would be collected by the MODIS oceans team and no funds are requested for P.I. support. This scenario avoids many of the biases in calibration traceability and intercomparisons, and will provide the a reliable basis for intercomparison of satellite sensors. It is important to note that the scientific satellite time series does not actually begin with instrument turn-on, but with the initialization effort. Direct funds to pay for ship time is the only way to provide flexibility in dealing with potentials of launch slip and the long advance time for scheduling UNOLS ship resources. This is similar to the method planned for SeaWiFS and MODIS initialization cruises. The cost estimate is based on 20 days of ship time at \$15K/day, which is a very minimal time.

N.W. Africa: Funds are requested to mount a dedicated cruise in 1996 off NW Africa to thoroughly investigate the impact of dust on both atmospheric and in-water algorithms. Funds from both FY95 and FY96 will go toward ship costs and P.I. costs. A cruise of 35 days (at 15K/day) with 5 investigators is envisioned. Assistance from MODIS, (ocean and atmospheres) and perhaps other agencies will be solicited. Further details are being worked, but the importance of the problems warrants such an effort.

Technology Exploitation

Optical drifter studies: Short term, expendable optical drifters appear to be an excellent way of obtaining validation observations of radiance ratios. Funds are included to purchase about 20/yr., for seeding by ships of opportunity in poorly sampled regions. Several investigations are currently underway which could provide the infrastructure for this at very little additional cost.

Automated towed systems: The funds would cover two projects to formulate and implement a system, using COTS components, to collect useful validation data from any of a number of opportunistic vessels and or platforms. Emphasis would be on data turn-around, and geographical breadth of coverage.

Optical mooring augmentation: Funds are requested to begin augmenting standard meteorological and oceanographic moorings with optical instruments (fluorometers, radiometers, absorbance

meters, as appropriate). Possible platforms include the TAO array, coastal towers and buoys. A feasibility study to instrument NDBC platforms is presently underway using NASA Ocean Biogeochemistry Program support. SIMBIOS support will permit a gradual ramp-up to a modest sustained number of stations.

Data Merger

The data merger component of SIMBIOS is the culminating step in the intercomparison process and is the synthesis of the calibration and validation efforts. As described in preceding sections, evaluation and implementation of binning schemes, the development and analysis of the Diagnostic Data Set and other related topics can be an involved process. The budget supports for 2 or 3 P.I.s outside the SPO to assist in this effort.

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TABLES

1. Ocean color sensor and coverage characteristics.
2. Calibration verification techniques: Applicability and Synergism.
3. Sun photometer and aureolometer network for aerosol characterization.
4. SIMBIOS Budget.

Characteristics of Ocean Color Sensors

Mission Instrument (launch)	Visible Bands (nm)	Resolution (km)	Swath (km)	Tilt (degrees)	Onboard Calibration	Data Collection (min/orbit)	Orbit Node (inclination)
ADEOS-I OCTS (1996)	412, 443, 490, 520, 565, 670, 765, 865	0.7	1400	0, ± 20	Solar Internal lamps	≈ 40	10:30 am descending
ADEOS-I POLDER (1996)	443, 490, 565, 670, 763, 765, 865, 910	6.2	2471	N/A	None	≈ 40	10:30 am descending
SeaSTAR SeaWiFS (1997)	412, 443, 490, 510, 555, 670, 765, 865	1.1 (LAC) 4.5 (GAC)	2800 (LAC) 1500 (GAC)	0, ± 20	Solar diffuser Lunar imaging	≈ 40 (GAC) < 1 (LAC)	12:00 noon descending
EOS MODIS (AM-1998) (PM-2001)	412, 443, 488, 531, 551, 667, 680, 748, 869 470, 555 670	1.0 0.5 0.25	1500	None	Solar diffuser (with stability monitor) Spectral Radiometric Calibration Assembly	≈ 40	10:30 ascending
EOS-AM MISR (1998)	440, 555, 670, 865	0.25	400	0, ± 26, ± 45, ± 60, ± 70	Solar diffuser	≈ 40	10:30 ascending
ENVISAT-1 MERIS (1999)	410, 445, 490, 520, 560, 620, 665, 681, 705, 754, 760, 765, 775, 855, 865, 900	0.3 (LAC) 1.2 (GAC)	1150	None	Solar diffusers (3)	≈ 20	10:30 descending
ADEOS-II GLI (1999)	380, 400, 412, 443, 460, 490, 500, 520, 545, 565, 600, 625, 667, 678, 710, 748, 760, 865	1.0	1600	0, ± 20	Solar diffuser Internal lamps	≈ 40	10:30 descending
MOS PRIRODA (launched Apr. 1996)	408, 443, 485, 520, 570, 615, 650, 685, 750, 815, 870, 945, 1010, 1600	0.7	80	None	Solar diffuser Internal lamps	Limited	Asynchronous (51.6°)

Mission Instrument (launch)	Visible Bands (nm)	Resolution (km)	Swath (km)	Tilt (degrees)	Onboard Calibration	Data Collection (min/orbit)	Orbit Node (inclination)
MOS IRS (launched Mar. 1996)	same as MOS-PRIRODA	0.5	200	None	Solar diffuser Internal lamps	Limited	10:30 descending
MSX UVISI (launched Apr. 1996)	400 bands (110-900 nm)	0.4 x 0.8	16	Pointable	None	Limited	Near sun-synchronous 3:30, progressively later
ROCSAT OCI (1998)	443, 490, 510, 555, 670, 865	0.8	600	None	None	Limited	Asynchronous (35°)
SAC-C MMRS 1998	490, 550, 660, 795, 1625	1.5	315	None	None	Limited	10:45 descending

Table 2. Calibration Verification Techniques: Applicability and Synergism

METHOD	RADIOMETRIC TERMS	ADVANTAGES	DISADVANTAGES
Internal Lamps	L_t	Only internal optics	Lamps degrade at unknown rate Not all optics included
Lunar	L_t, L_{surf}	No atmospheric radiances Lunar surface relatively constant	Lunar surface reflectances not well known & require corrections for libration Relatively infrequent observations (monthly)
Solar	L_t, L_{surf}	No atmospheric radiances Frequent observations	Diffuser surface degrades
High Altitude Vicarious	L_t, L_r, L_{surf}	Relatively simple atmospheric correction If clear lake, $L_{surf}=L_w$; should be easily determined	If land, L_{surf} must be characterized
Cloud Top Vicarious	L_t, L_r, L_{surf}	Provides most frequent observations Primarily for relative band-to-band calibration	Assumes uniform spectral & bidirectional reflectances Provides information only at high radiance levels
Sea Level Vicarious	$L_t, L_r, L_{ra}, L_a, L_w$	If buoy, provides fairly frequent observations (weekly) If in clear water, L_w should be easily determined If distant from land, L_{ra} and L_a should be relatively easy to determine	If buoy, accurate long term L_w time series requires periodic instrument servicing Requires most complex atmospheric correction

Table 3. Sun photometer & aureolometer network for aerosol characterization. While listings for La Jolla, Lanai and Wallops are shown, the status and durations are uncertain. Therefore, SIMBIOS would plan to instrument those sites in case the other activities are not supported.

Status	Station Name	Device	P.I.	Duration
Highly Certain				
	Barbados	CIMEL	Tanre	7/95 -
	Bermuda	CIMEL	Frouin	6/95 -
	Capo Verde	CIMEL	Tanre	10/94 -
	Dakar	CIMEL	Tanre	1/96 -
	Dry Tortugas	CIMEL	Gordon/Voss	6/95 -
	Hawaii (Lanai ?)	CIMEL	Frouin	7/95 -
	La Jolla	CIMEL	Frouin	?
	Wallops	CIMEL	Holben	7/95 -
	Niigata	PREDE	Nakajima	?
	Okinawa	PREDE	Nakajima	?
	Cape Grim, Australia	?	CSIRO	?
	Guadeloupe	CIMEL	Tanre	1/96 (?)
	Tenerife	CIMEL	Tanre	7/96
Proposed				
	ARM (W. Eq. Pac.)	?	?	?
	Reunion	CIMEL	Tanre	?

Table 4. SIMBIOS Budget

Comments

Element/Item	FY95	FY96	FY97	FY98	FY99	
SIMBIOS Project (Total manpower = 21 FTEs)						
Project Management						
Admin. Assist. (1 contractor)	55	55	55	55	55	
Equipment & supplies	25	25	25	25	25	
Meeting support	25	25	25	25	25	
Documentation (inc. tech. ed.)	70	70	70	70	70	
Calibration (analyst & post-doc)	125	125	125	125	125	
Validation (2 analysts & post-doc)	200	200	200	200	200	
Data processing (7 staff)	500	500	500	500	500	
Data processing (H/W, etc.)	1500	250	500	250	250	
Data merger (analyst & post-doc)	125	125	125	125	125	
On-site manpower costs	126	126	126	126	126	
Subtotal	2751	1501	1751	1501	1501	
				Total	9005	
Calibration						
Satellite Cal. Scale Traceability						
Round robins (2/yr)	150	150	150	150	150	NIST
Stability monitors	150	50	50	50	50	Contract
Community calibration support	200	200	200	200	200	NRA
Special studies	100	350	350	350	350	NRA
High lat. cal. & val. verification	700	700	700	700	700	NRA
High altitude vicarious calibration	200	200	200	200	200	NRA
Common atmos. corr. implementation	150	150	150	150	150	Contract
Subtotal	1650	1800	1800	1800	1800	
				Total	8850	
Validation						
Sun photometer support	150	150	150	150	150	NRA
Field studies						
Productivity time series	250	250	250	250	250	NRA
Augment of U.S. programs	400	400	400	400	400	NRA

Table 4. SIMBIOS Budget

Comments

PML/AMT	250	250	250	250	250	NRA
High latitude studies	Included in Calibration line above					
Initialization cruise augment.	0	300	0	0	600	MODIS oceans team
N.W. Africa	500	500	0	0	0	NRA
New technology exploitation						
Optical drifter studies	150	150	150	150	150	NRA
Automated towed systems	350	150	150	150	150	Contract
Optical mooring augmentations	250	250	250	250	250	
Subtotal	2300	2400	1600	1600	2200	
				Total	10100	
Data merger						
Algo. dev. & val. studies	150	150	150	150	150	NRA
Subtotal	150	150	150	150	150	
				Total	750	
Total	6851	5851	5301	5051	5651	
				Grand Total	28705	

APPENDIX A: Lexicon of Calibration/Validation Terminology

Bio-optical: A term that refers to any in water quantity that can affect or be derived from the water leaving radiances. This term is used to differentiate in water products from others such as aerosol products which are classified as geophysical.

Instrument Characterization: The process of understanding in a quantitative sense the operation of the instrument and its response as a function of operating and viewing conditions. This includes determining temperature coefficients, scattering, stray light and ghost effects, polarization, stability, band passes, fields of view, channel to channel and detector to detector biases and differences, noise levels, electronic processing characteristics, optical transfer, the optimal operating envelop, failure modes, etc.

Calibration: The process of determining the functions and coefficients necessary to convert instrument output values (voltages or counts) to radiometric units (in this case watts/m²-um-sr). Both radiometric and spectral responses are implicit. It consists of pre-launch and on-orbit components, and direct and vicarious methods. In addition to establishing the instrument counts to radiance relationship, calibration deals its temporal and orbital variations. Both characterization and calibration apply to in situ and airborne instrumentation used for vicarious calibration and validation data collection, as well as the satellite sensor. A key component is the maintenance of the calibration scale throughout the mission life, be it referenced to primary standards or the sun.

Vicarious Calibration: A subset of calibration wherein the information used to establish the counts/radiance relationships and proportionality constants are derived from the sensor in orbit along with independent measurements of biological and geophysical variables and radiometric models, rather than primary, secondary, or higher order standards (direct calibrations). An example is the atmospheric inversion technique that makes use of in situ radiance or reflectance measurements and radiative transfer theory to compute what the satellite sensor should have measured for total radiance in a given situation, in order to verify direct or on-orbit calibration. As with direct calibration, a detailed analysis of the expected uncertainty is an integral component of the analysis. For sensors without robust on-board direct calibration, vicarious techniques are the only ones available for monitoring calibration accuracy over the mission lifetime.

Initialization: The process of carrying out vicarious calibration for a newly-launched sensor, prompted by the fact that it is reasonable to expect that the stresses associated with launch may alter radiometric calibration. On this basis, the sensor calibration is revised to provide agreement with the vicarious calibration exercise.

Calibration Fine Tuning: The vicarious calibration of a sensor resulting from an initialization exercise may still contain significant uncertainty. Because of errors in the atmospheric correction and in the calibration, there are expected to be small systematic biases in the retrieved water-leaving radiances and the higher level products, e.g., the pigment concentration. Calibration fine tuning refers to the process of further altering the sensor calibration (within the limits of the vicarious calibration uncertainty) to remove any long-term biases in the retrieved product. Clearly, the most desirable product with which to perform this fine tuning is the water-leaving radiance. Surface measurements for this purpose will be available at the MOBY site off Hawaii on a continuous basis in the SeaWiFS/MODIS era.

Quality Assurance/Quality Control: The process of assuring that data products are what they are claimed to be. This is principally a task of making sure that a given geophysical field is the correct one (e.g., that data labeled band 1 is band 1 and not some other band), that the software and processing system worked (the file is not filled with zeros or negative radiance, etc.). It is not a validation procedure as defined below.

Validation (Data Product Validation): The process of determining the spatial and temporal error fields of a given remotely sensed data product through a comparison with values derived from sampling at the surface, examination of the internal consistency of the data product, and/or comparison with modeled surrogates. The robustness of the validation program is primarily a function of the quality, sampling, and coverage of the data used for comparison. In some cases where the physics is very simple and predictable (all sources of error easily determined and predicted), validation at a few locations and times may be sufficient to provide good estimates of errors in all places and times. In other cases where the temporal and spatial variability of the product, input fields, and algorithm error budgets, are poorly known, the breadth of the validation process must be considerably larger and ongoing.

Algorithm: The set of equations, computer code, and methodology used to derive biological, chemical and geophysical variables, fields or parameters from calibrated satellite observations.

Verification: A major tenet of science is independent verification of results by another investigator. In this context, verification could refer to independent validation, characterization, calibration, or processing code or methodology. It can use the same, or different data, and can result in positive or negative results. It may result in a modification of the algorithm, or provide the basis for an entirely different approach. Verification is also used to denote the paper trail traceability of calibration.

Stability: Stability in this context refers to how well the time dependency of calibration is understood, and is essentially an indication of temporal precision in the level-1B product over time. For detection and monitoring of long term trends, stability of the level-1B product may be of higher importance than its absolute accuracy.

APPENDIX B: Agreements for Access to U.S. and Foreign Ocean Color Data

1. Access to U.S. Ocean Color Data

a) Coastal Zone Color Scanner (CZCS): NASA Instrument aboard Nimbus-7 satellite, provided data from 1978 to 1986.

Available to any requester at the lowest possible cost, not to exceed the marginal cost of fulfilling the individual user request. Full data set available from GSFC DAAC; 9 other archives holding level-1 and -2 (reduced resolution) and level-3 data.

b) Sea-Viewing Wide-Field-of-view Sensor (SeaWiFS): NASA Instrument aboard Orbital Science Corporation (OSC) SeaStar Spacecraft, scheduled to be launched in September 1995.

NASA has contracted with OSC for the research use of a 5-year ocean color data set;

Researchers may request and be granted authority by NASA to directly receive encrypted data (1 km resolution) broadcast by the SeaStar satellite as it passes overhead. Stations licensed by NASA under this arrangement receive decryption codes to permit data processing 2-4 weeks following data acquisition;

Redistribution by researchers is limited to other NASA-approved researchers;

Under special circumstances, NASA may grant a temporary (2 week) real-time license to a ground station for support of specific authorized research users; and

Operational and commercial users must apply for a license to OSC directly.

2. Access to Foreign Ocean Color Data

a) Ocean Color Temperature Scanner (OCTS): NASDA instrument aboard Japanese Advanced Earth Observing Satellite (ADEOS), scheduled to be launched in 1996.

Data exchange as per IEOS data exchange principles included as part of the NASDA-NASA ADEOS MOU;

All ADEOS data available to NASA and NOAA and their designated users at the lowest possible cost for non-commercial use in the following categories: research, applications, and operational use for the public benefit; and

Users for research and applications are selected through Announcements of Opportunity or similar processes.

b) POLARization and Directionality of the Earth's Reflectance (POLDER): CNES Instrument aboard the Japanese Advanced Earth Observing Satellite (ADEOS), scheduled to be launched in February 1996.

NASDA-CNES MOU for POLDER defines POLDER data policy;

NASDA-NASA MOU provides U.S. access to all ADEOS data consistent with IEOS data exchange principles and NASDA-CNES MOU;

POLDER standard products will be available for the following non-commercial uses: internal NASDA and CNES use; use by international POLDER Science Team; and other non-commercial data use;

All POLDER data provided to users for non-commercial data use is provided under a standard "license for use". This license protects against distribution to third parties and unauthorized use (i.e. commercial use); and

POLDER standard products will be made available to users for non-commercial data use at no more than the marginal cost of fulfilling the specific user request (members of the POLDER Science Team receive data and products free of charge).

c) Modular Optoelectronic Scanning Spectrometer (MOS A/B): DARA instrument aboard Russian Priroda module on Mir, scheduled to be launched in December 1995.

Priroda currently available only to Principal Investigators; and

NASA interested in obtaining data via NASA-DARA agreement.

d) Medium Resolution Imaging Spectrometer (MERIS): ESA instrument aboard ESA ENVIRONMENTAL SATellite (ENVISAT), scheduled to be launched in 1998.

NASA and ESA will complete an agreement providing for the exchange of ENVISAT and EOS AM-1 data, based on the IEOS data exchange principles.

e) GLobal Imager (GLI): NASDA instrument aboard Japanese Advanced Earth Observation Satellite-2 (ADEOS-2), scheduled to be launched in 1999.

NASA-NASDA ADEOS-2 MOU, incorporating IEOS data exchange principles, is in negotiation.

3. Other Cooperation

NASA-NASDA Ocean Color Collaboration

May 5, 1994, NASA/Kennel letter to NASDA/Tateno proposing closer collaboration in the area of ocean color research. Specific areas identified include:

Regional distribution by NASDA to researchers of SeaWiFS LAC data received at Japanese institutions under license from NASA, and GAC data received by NASA. Researchers must receive license from NASA;

Regional distribution by NASA to researchers of OCTS LAC and GAC data. Researchers must receive license from NASDA;

Development of coordinated plan for joint in-flight calibration and validation, and pre-flight cross-calibration between the two instruments;

Development of a joint field program aimed at validating the sensors, developing oceanic and atmospheric algorithms for processing the data, and developing applications;

Exchange of ancillary data, including hydrographic profiles, wind fields, and other relevant data necessary for proper adjustment of regional atmospheric and bio-optical algorithms; and

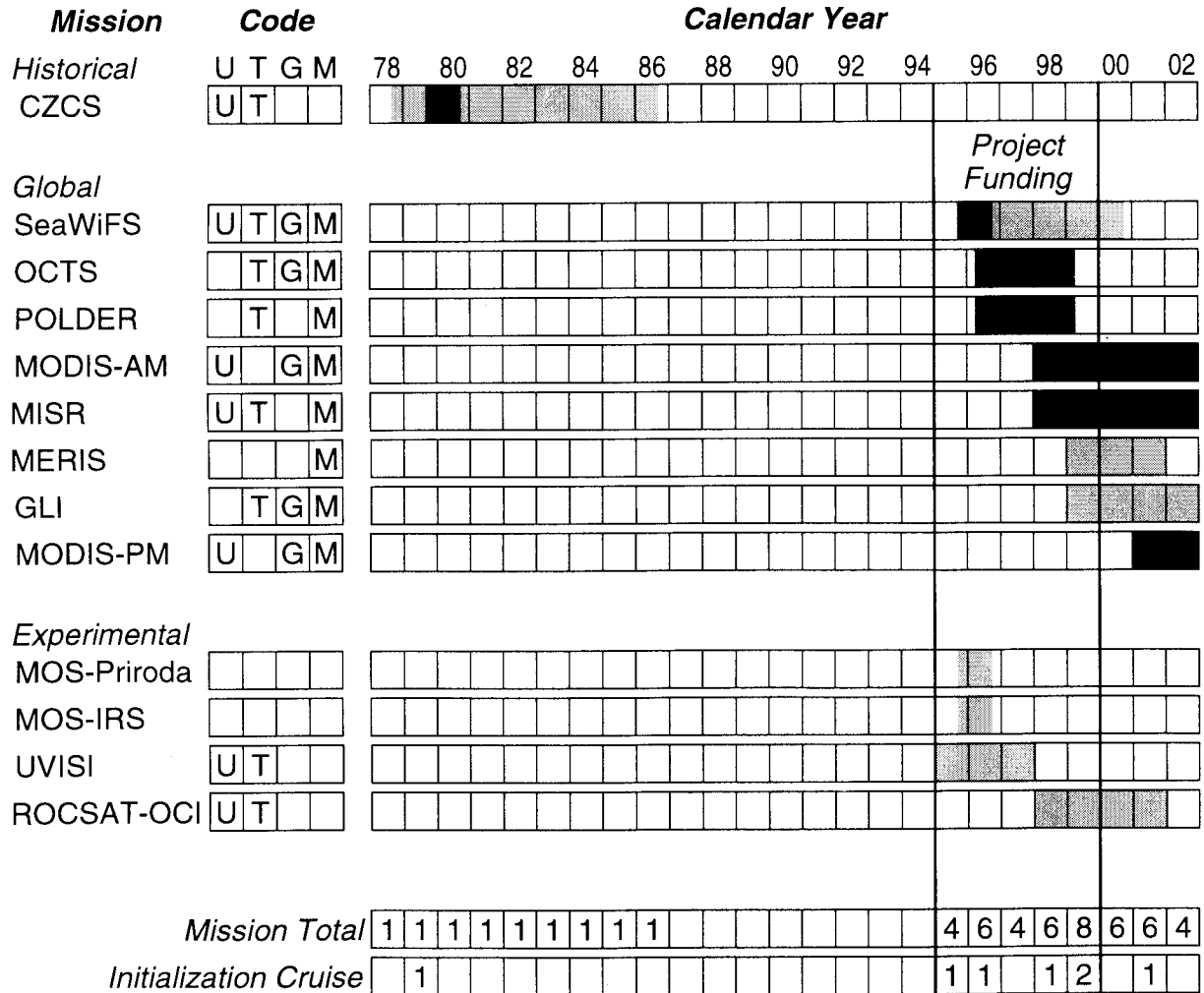
All aspects to be coordinated through joint science team meetings.

FIGURES

1. Ocean color mission launch and operation time lines. The Codes are D (Domestic or U.S.), T (sensor Tilts for sun glint avoidance), G (routine Global data collection) and M (mission has a robust calibration and validation program that Meets the paradigm illustrated in Figure 4).
2. Estimated 4-day total meridional coverage distribution for various combinations of MODIS-AM (10:30), -PM (1:30) and EOS Color (12:00, 705 km). The analysis was performed for the spring equinox and utilized climatological winds and clouds. Coverage enhancements by multiple satellites can be achieved in a variety of ways including (1) complementing nontilting instruments with tilted sensors (sun glint avoidance), (2) combining ascending and descending orbits (avoids redundant swaths even with similar equatorial crossing times) and (3) offsetting equatorial crossing times (time separation). While the particular analyses shown was derived for EOS Color which is no longer in the EOS launch manifest, the analyses are valid for any noon time mission having a wide field of view. It should be noted that not all combinations of the sensors listed as “Global” in Figure 1 result in significant increases in coverage over what a single sensor would obtain because they do not satisfy one of these three criteria.
3. Flow diagram showing evolution and refinement process for ocean color products.
4. The calibration and validation paradigm for ocean color. The diagram identifies the radiative transfer components and various observations required to develop the atmospheric correction and bio-optical algorithms as well to evaluate the post-launch sensor calibration. The terms are L_t (total radiance), L_a (aerosol radiance due to particulate scattering), L_r (Rayleigh radiance due to scattering by gases), L_{ar} (radiance due to Rayleigh and aerosol scattering interactions), t (atmospheric transmittance), and L_w (water-leaving radiance). O_2 and O_3 are explicitly identified because of absorption by these gases at wavelengths commonly used by ocean color sensors.
5. Key calibration sites (serve for validation as well).
6. Locations of sun photometer sites. Only coastal sites are shown and most are supported by other programs. SIMBIOS would support sites in Hawaii, La Jolla and Wallops Island.
7. Key validation sites for water-leaving radiances and bio-optical properties. Most of the activities identified are augmentations or collaborations with other agencies, countries or NASA programs which cover the majority of the costs. These are identified with each site.
8. The primary components of ocean biogeochemistry mission calibration comparison and data merger program and a strawman organizational structure.
9. Implementation schedule for the project elements.

Figure 1

A Timeline of Ocean Color Missions



Code

- U U.S. Mission
- T Tilted Views
- G Global Coverage
- M Meets calibration and validation paradigm

Key

- █ Instrument and/or Science Team
- █ No Defined Team(s)

Figure 2

Latitudinal Coverage (705 Km EOS-Color)

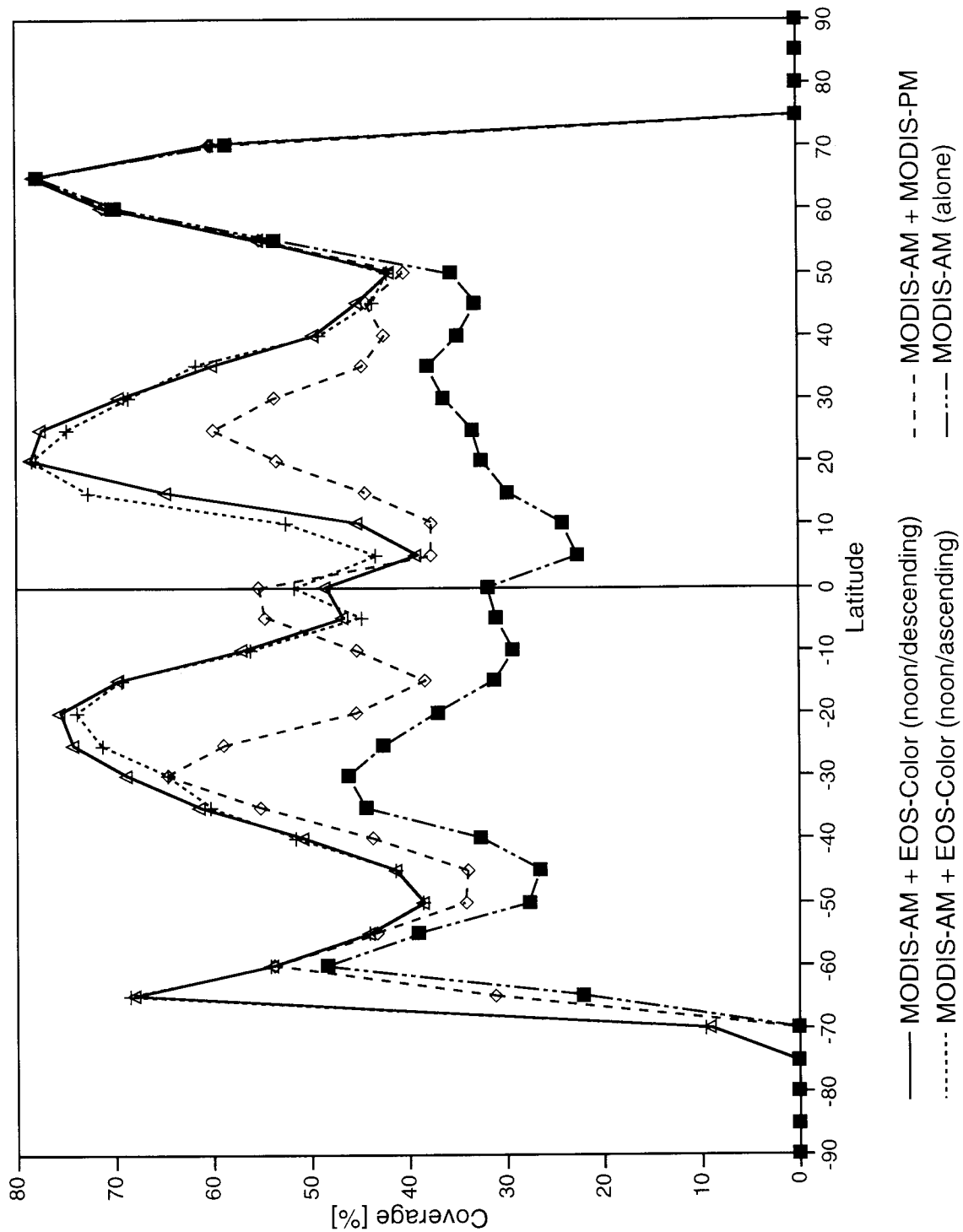


Figure 3

Ocean Color Product Evolution and Refinement

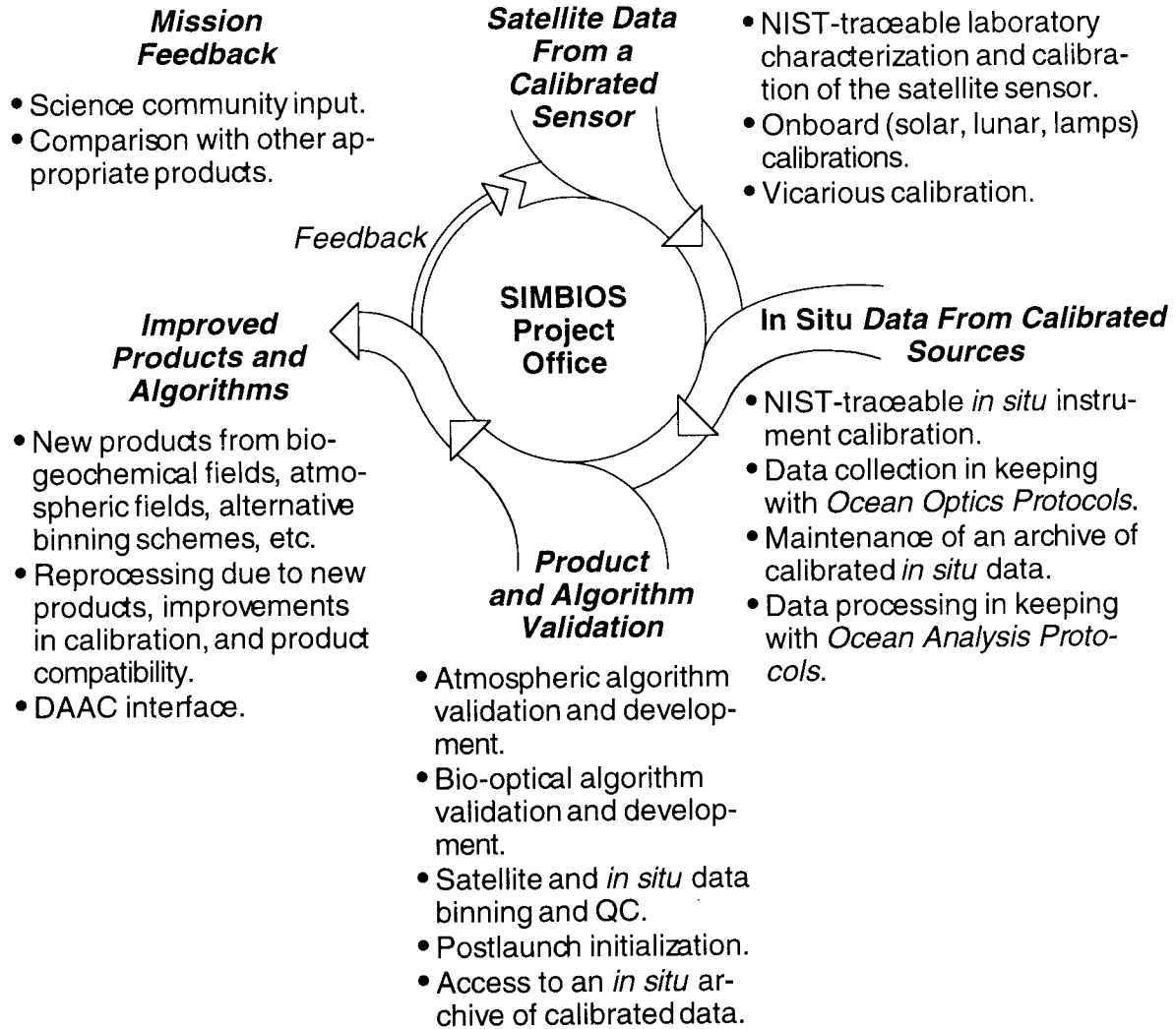
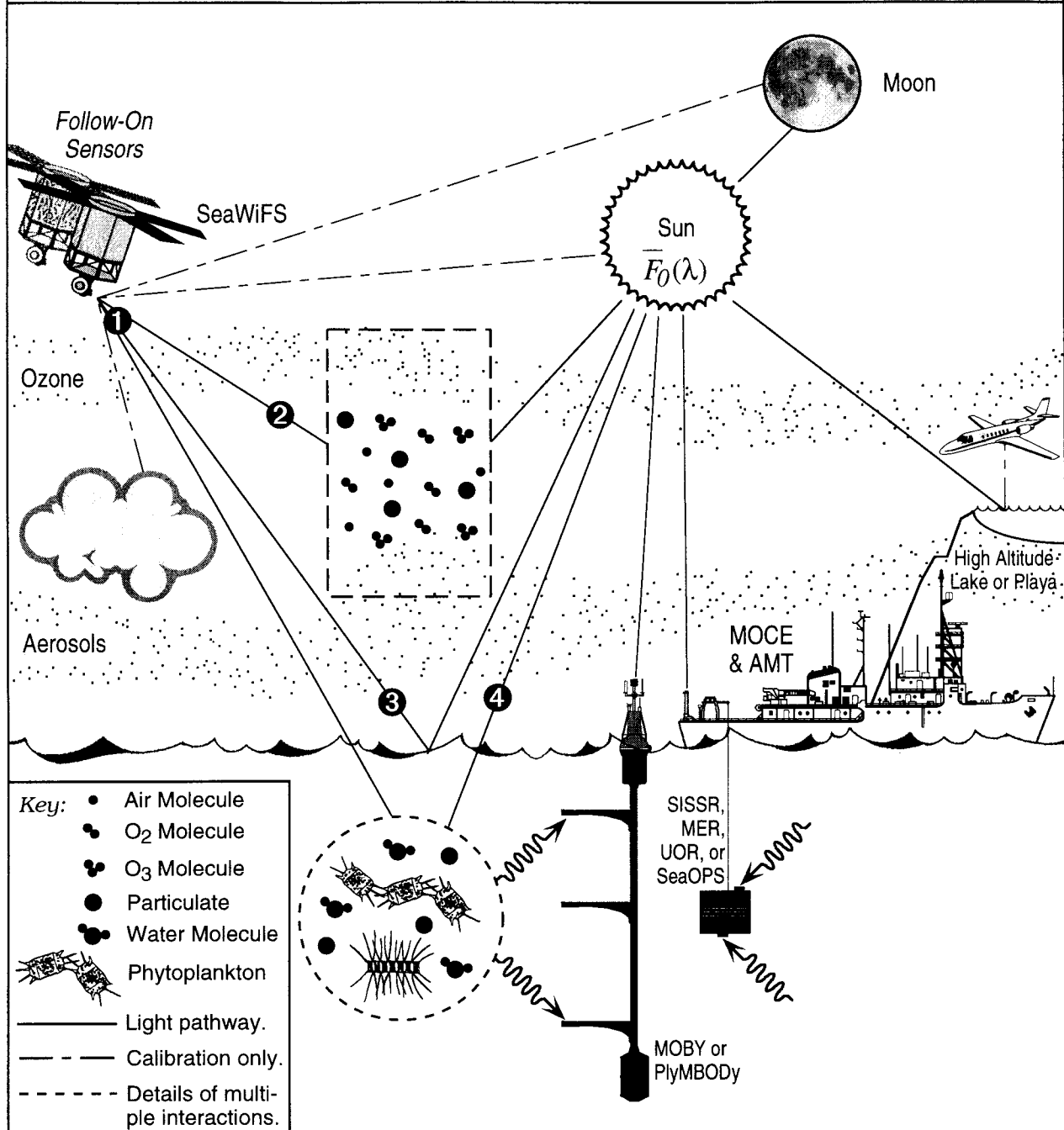


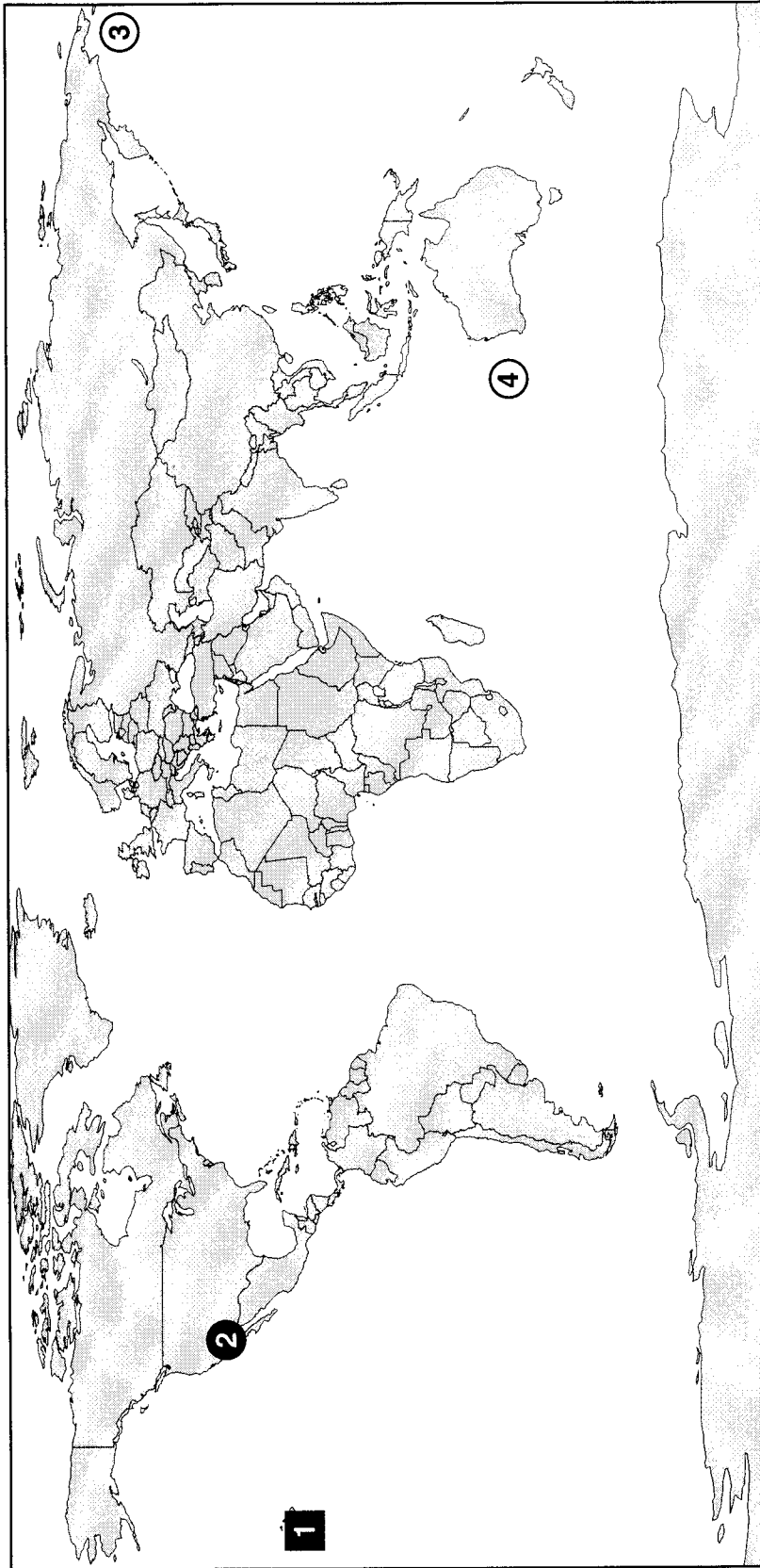
Figure 4

Ocean Color Calibration and Validation Paradigm

$$\underbrace{L_t(\lambda)}_{\text{① On Orbit}} = \underbrace{L_a(\lambda) + L_r(\lambda) + L_{ar}(\lambda)}_{\text{② Atmospheric}} + \underbrace{t(L_g(\lambda) + L_f(\lambda))}_{\text{③ Sea Surface}} + \underbrace{tL_w(\lambda)}_{\text{④ In Situ}}$$



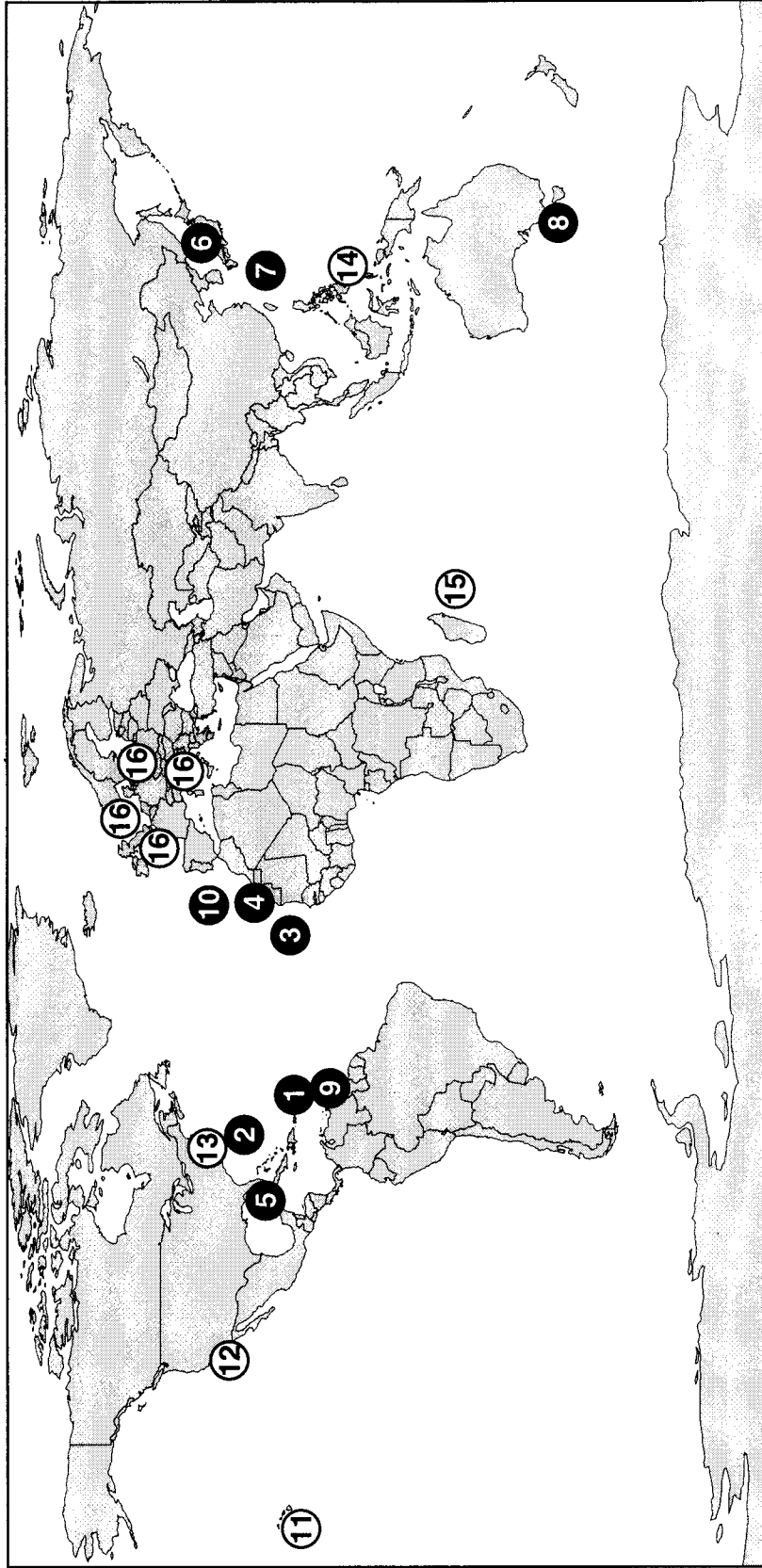
Calibration and Initialization Sites in Support of SIMBIOS



- Calibration and Initialization Site
- Calibration Site
- Proposed Calibration Site
- 1** MOBY (Lanai, HI)
- 2** High Altitude (Lake or Playa)
- 3** High Latitude (Northern Hemisphere)
- 4** Southern Ocean

Figure 5

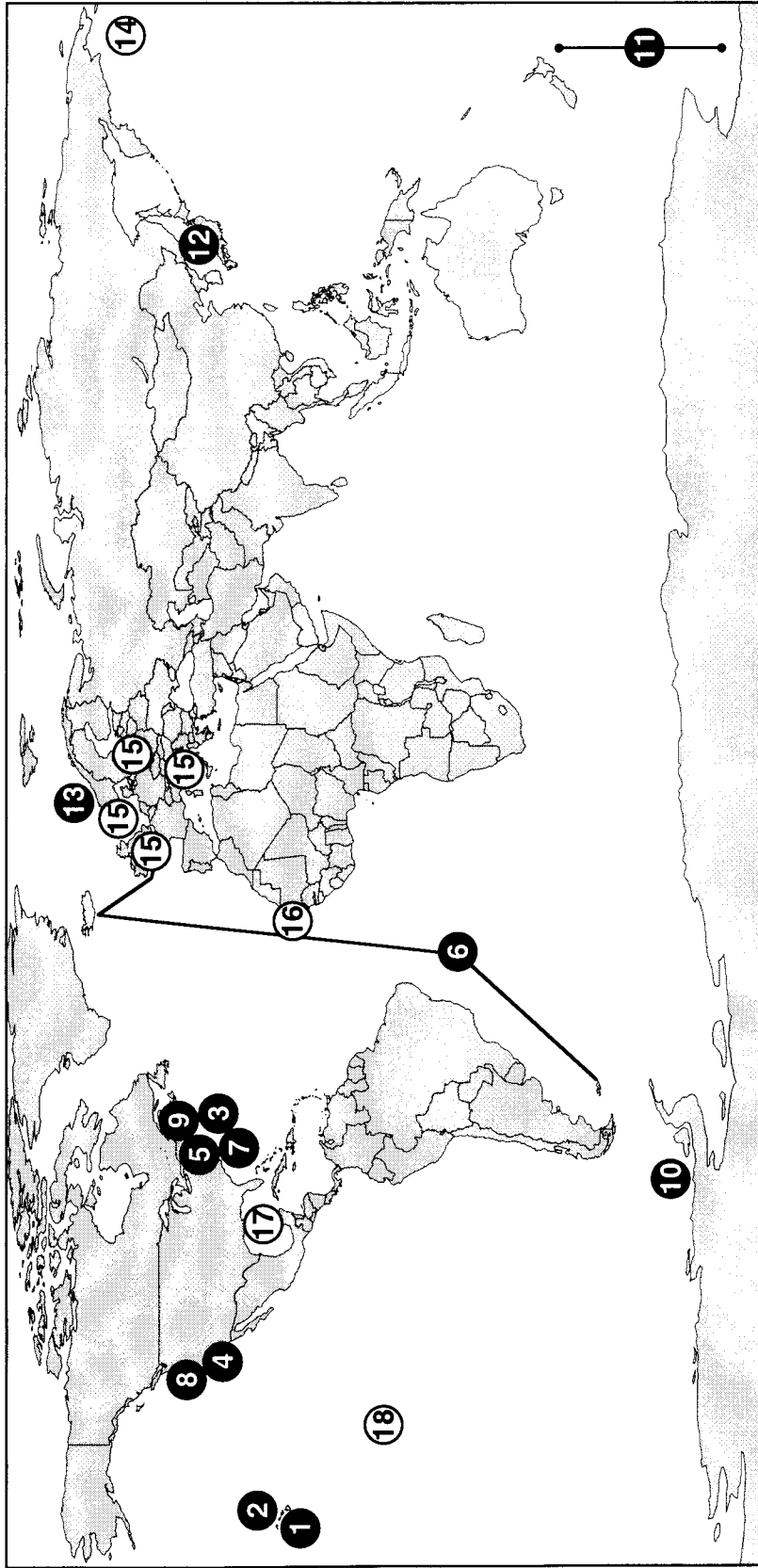
Coastal and Island Sun Photometer Sites



- | | | | |
|----------------|--------------|-----------------------|-----------------|
| 1 Barbados | 6 Niigata | 11 Lanai (SIMBIOS) | 16 PICASSO |
| 2 Bermuda | 7 Okinawa | 12 La Jolla (SIMBIOS) | |
| 3 Cape Verde | 8 Australia | 13 Wallops (SIMBIOS) | |
| 4 Dakar | 9 Guadeloupe | 14 ARM | ● Existing Site |
| 5 Dry Tortugas | 10 Tenerife | 15 Reunion | ○ Proposed Site |

Figure 6

In-Water Validation Sites and Regions

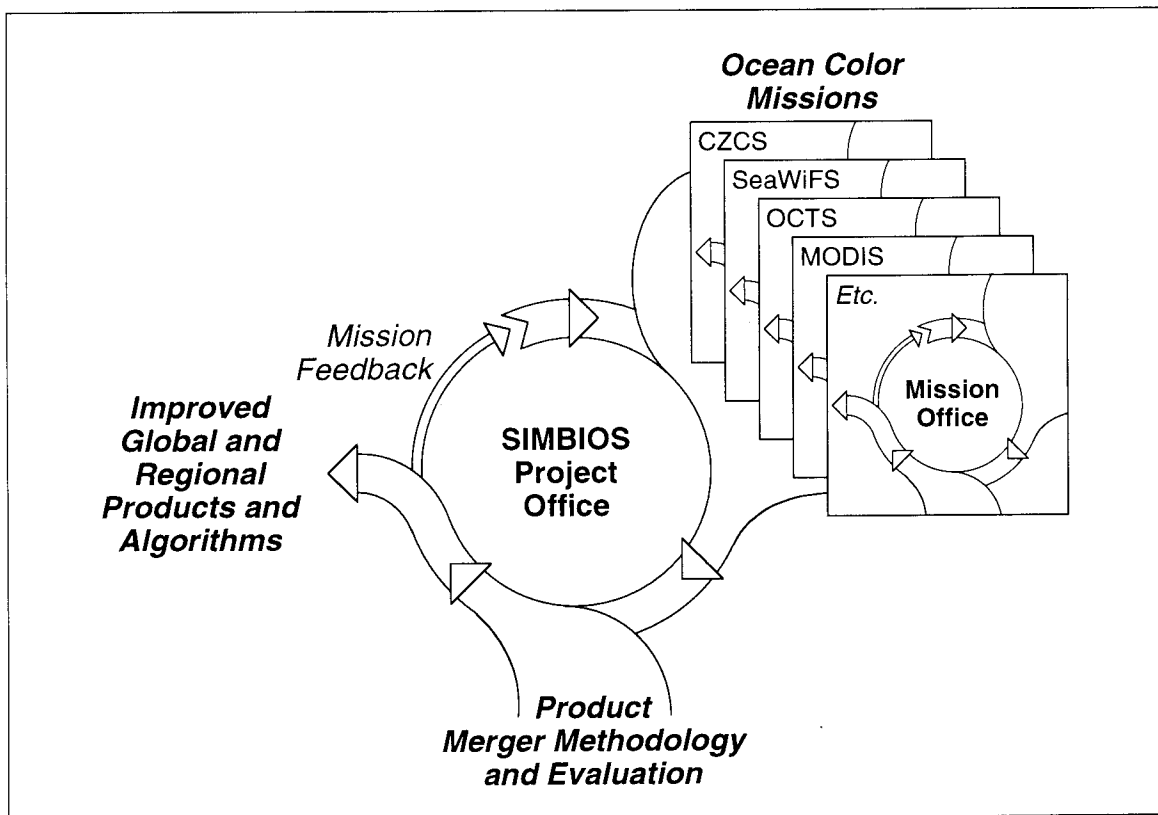


- | | | | |
|-------------------------|--|-----------------------------------|------------|
| 1 MOBY (NASA) | 7 Ocean Margins Program (DOE) | 13 Norwegian Studies | ○ Proposed |
| 2 HOTS (NSF) | 8 Monterey Bay (MBARI) | 14 High Latitude (SIMBIOS) | ● Existing |
| 3 BATS (NSF) | 9 Coastal Mixing & Optics (ONR) | 15 PICASSO (European) | |
| 4 CalCoFI (NOAA) | 10 LTER (NSF) | 16 NW Africa (SIMBIOS) | |
| 5 LMER (NOAA) | 11 JGOFS (NSF) | 17 Gulf of Mexico (NASA) | |
| 6 BAS (UK) | 12 YBOM (Japan) | 18 MBARI TAO (NASA) | |

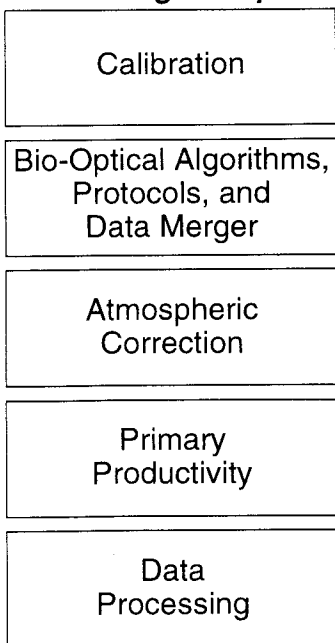
Figure 7

Figure 8

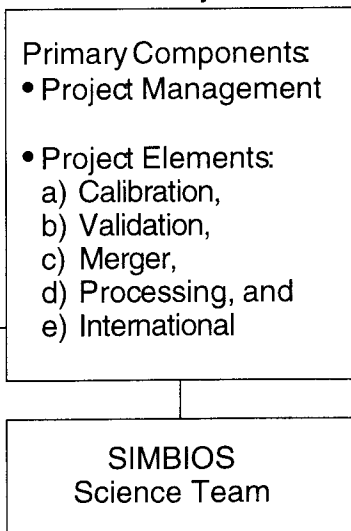
The Primary Components of SIMBIOS



Working Groups



SIMBIOS Project Office



External Groups

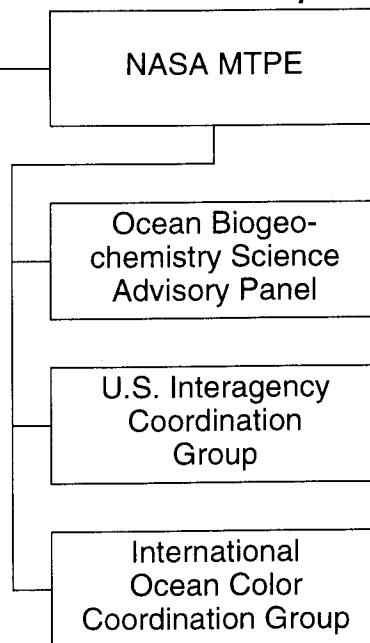
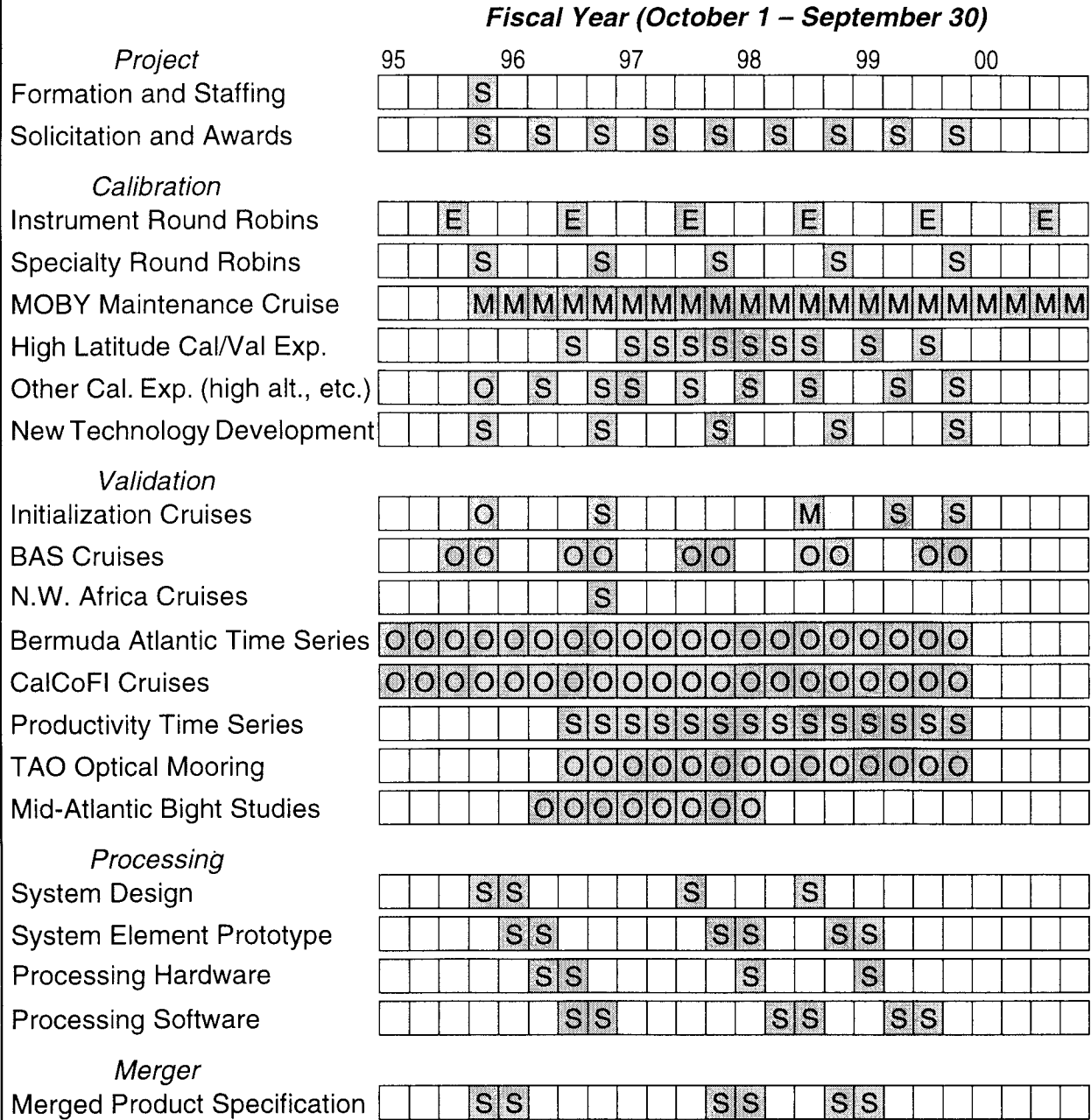


Figure 9

Implementation Schedule for SIMBIOS Elements



Key: Primary Funding Source

M MODIS Oceans Project

E Other EOS Projects

S SIMBIOS Project

O Other Projects

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) As a result of the Earth Observing System (EOS) restructuring exercise during the last half of fiscal year 1994, the EOS Color mission, which was scheduled to be a data-buy with a 1998 launch was dropped from the EOS mission manifest primarily because of the number of international ocean color missions scheduled for launch in the 1998 time frame. In lieu of a new mission, NASA Goddard Space Flight Center (GSFC) was tasked by NASA Headquarters to develop an ocean color satellite calibration and validation plan for multiple sensors. The objective of the activity was to develop a methodology and operational capability to combine data products from the various ocean color missions in a manner that ensures the best possible global coverage and data quality. The program was called the Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) project coined from the biological term "symbiosis." This document is the original proposal that was developed and submitted in May 1995. SIMBIOS was approved in 1996 and initiated in 1997 with a project office and technical staff at GSFC and a science team to assist in the development of validation data sets, sensor calibration, atmospheric correction, and bio-optical and data merger algorithms. Since its inception, the SIMBIOS program has resulted in a broad-based international collaboration on the calibration and validation of a number of ocean color satellites.				
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