NASA Technical Memorandum 104566, Vol. 3

SeaWiFS Technical Report Series

Stanford B. Hooker and
Elaine R. Firestone, Editors

Volume 3, SeaWiFS Calibration and Validation Plan

Charles R. McClain, Wayne E. Esaias,
William Barnes, Bruce Guenther,
Daniel Endres, Stanford B. Hooker,
B. Greg Mitchell, and Robert Barnes

September 1992

NASA Technical Memorandum 104566, Vol. 3

SeaWiFS Technical Report Series

Stanford B. Hooker, Editor
NASA Goddard Space Flight Center
Greenbelt, Maryland

Elaine R. Firestone, Technical Editor
General Sciences Corporation
Laurel, Maryland

Volume 3, SeaWiFS Calibration and Validation Plan

Charles R. McClain, Wayne E. Esaias,
William Barnes, Bruce Guenther,
Daniel Endres, and Stanford B. Hooker
NASA Goddard Space Flight Center
Greenbelt, Maryland

B. Greg Mitchell
National Aeronautics and Space Administration
Washington, D.C.

Robert Barnes
CHEMAL, Inc.
Wallops Island, Virginia

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

1992

PREFACE

Experience with the Coastal Zone Color Scanner (CZCS) and other satellite sensors has underscored the importance of sustained and coordinated programs to verify sensor calibration and derived products, especially as more rigorous specifications on measurement accuracies are required to address the geophysical and biological problems that have been identified by the science community.

As a second generation ocean color instrument, SeaWiFS offers a variety of design improvements over the CZCS, which should provide the capability to meet the mission objectives. This document outlines the calibration and validation program designed by members of the SeaWiFS Project Office (SPO) in consultation with the SeaWiFS Prelaunch Science Working Group (SPSWG) and others. The program accelerates a number of activities already being conducted by some members of the Moderate Resolution Imaging Spectrometer (MODIS) Instrument Team and incorporates a number of additional functions. The program is meant to initiate a long-term strategy for the calibration and verification of a sequence of ocean color missions scheduled for launch during this decade and the next. Given the fiscal contraints within which the SPO must work, we feel it is as comprehensive a program as can be implemented.

This plan was submitted to the SPO in early January 1992, but because of the rapid pace of activities within the SPO, no attempt has been made to keep the document current. Therefore, some information is dated, and some minor inconsistencies are present. The strategies, however, that are outlined remain the same and significant progress has been made in executing each of the program elements. For example, all primary sole source contracts, cooperative agreements, and memoranda of understanding required to execute the *in situ* observation, algorithm development, and round-robin instrument calibration programs have been finalized. As the calibration and validation program procedes, progress will be documented in subsequent volumes of the SeaWiFS Technical Report Series. For instance, the proceedings of the Monterey Workshop on instrument calibration and data collection protocols is Volume 5 of the series and has already been published out of sequence due to the demand for it by the science community.

The progress of the calibration and validation program is reported to the SPO during quarterly reviews. To date, reviews have been held in February, May, and August 1992, at the NASA/Goddard Space Flight Center (GSFC). This review schedule will be maintained as long as the SPO deems necessary. These reviews are open sessions and those interested in the program are encouraged to attend. The schedule and agenda for these reviews are distributed via electronic mail. If anyone is not currently being notified, please let the SPO know that you wish to be added to the mailing list.

Those of us in the SPO view the SeaWiFS mission as a collaboration with the ocean color community and we are looking forward to working closely with them. The ocean color community has worked long and hard for this mission and it is our expectation that together, we can make SeaWiFS a great success.

Greenbelt, Maryland —C. R. M.
August 1992

Abstract

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) will be the first ocean color satellite since the Nimbus-7 Coastal Zone Color Scanner (CZCS), which ceased operation in 1986. Unlike the CZCS, which was designed as a proof-of-concept experiment, SeaWiFS will provide routine global coverage every two days and is designed to provide estimates of photosynthetic pigment concentrations of sufficient accuracy for use in quantitative studies of the ocean's primary productivity and biogeochemistry. A review of the CZCS mission is included that describes the limitations of that data set and provides justification for a comprehensive SeaWiFS calibration and validation program. To accomplish the scientific objectives of the mission, the sensor's calibration must be constantly monitored, and robust atmospheric correction and bio-optical algorithms must be developed. The plan incorporates a multi-faceted approach to sensor calibration using a combination of vicarious (based on *in situ* observations) and onboard calibration techniques. Because of budget constraints and the limited availability of ship resources, the development of the operational algorithms (atmospheric and bio-optical) will rely heavily on collaborations with the Earth Observing Satellite (EOS), the Moderate Resolution Imaging Spectrometer (MODIS) oceans team, and projects sponsored by other agencies, e.g., the United States Navy and the National Science Foundation (NSF). Other elements of the plan include the routine quality control of input ancillary data (e.g., surface wind, surface pressure, ozone concentration, etc., used in the processing and the verification of the level-0 (raw) data to level-1 (calibrated radiances), level-2 (derived products) and level-3 (gridded and averaged derived data) products.

---

1. INTRODUCTION

The program for SeaWiFS calibration and validation reflects the experience that too often, missions have focused on the engineering aspects of a flight program and have not adequately addressed issues of sensor performance after launch and algorithm development. The SeaWiFS Project Office (SPO) will incorporate a variety of activities, both in the prelaunch and post-launch periods, designed to ensure that the performance of the instrument is accurately quantified throughout the mission and the products the SPO generates meets the requirements of the scientific community. This document outlines the various components of the calibration and validation effort. It is important to note the length of time between the formation of the SPO and the launch of SeaWiFS is less than two years. This is a relatively short amount of time to prepare for a mission and will require a concerted effort on the part of the National Aeronautics and Space Administration (NASA) and the science community in partnership.

1.1 Historical Perspective

The Nimbus-7 Coastal Zone Color Scanner (CZCS) was launched in October 1978, and was the first satellite sensor designed specifically for the estimation of pigment concentrations in the ocean. The mission was designed as a proof-of-concept experiment and had narrowly defined objectives, namely, a limit of 2 hours of coverage per day, a 1 year demonstration lifetime, and a 10% level-2 data processing goal (Hovis et al. 1980 and Hovis 1981). Table 1 provides the design characteristics of the CZCS.

Table 1. Major instrument parameters and characteristics of the CZCS ocean color sensor (from Ball Aerospace, 1979).

Instrument Bands				
Band	Wavelength FWHM [nm]	Saturation Radiance[1]	Input Radiance[1]	SNR[2]
1	433–453	11.4	8.41	350
2	510–520	8.0	5.44	342
3	540–560	6.4	4.45	280
4	660–680	2.9	2.60	209
5	700–800	24.0	1.61	50
6	10,500–12,500	*N/A SST Applications Only*		
Sensor Accuracy				
Radiance Accuracy:	5%			
Band Registration:	<0.1 pixel			
Location Knowledge:	~2 pixels			
Saturation Recovery:	~100 pixels			
Polarization:	<2%			
Nadir Resolution:	0.825 km LAC			
Mission Characteristics				
Orbit Type:	Sun Synchronous at 955 km			
Equator Crossing:	1130 ±25 min., ascending			
Duty Cycle:	<10%			
Swath Width:	1,800–1,600 km LAC (±20°)			
Scan Plane Tilt:	+20° to −20° in 2° steps			
Dynamic Range:	8 bits quantization; 4 gains			

1. Units of $\mathrm{mW\,cm^{-2}\,\mu m^{-1}\,sr^{-1}}$; gain 1.
2. Measured at input radiances.

The bio-optical and atmospheric correction algorithms for the CZCS were developed after launch (Clark 1981, Austin and Petzold 1981, Gordon et al. 1983a, and Gor-

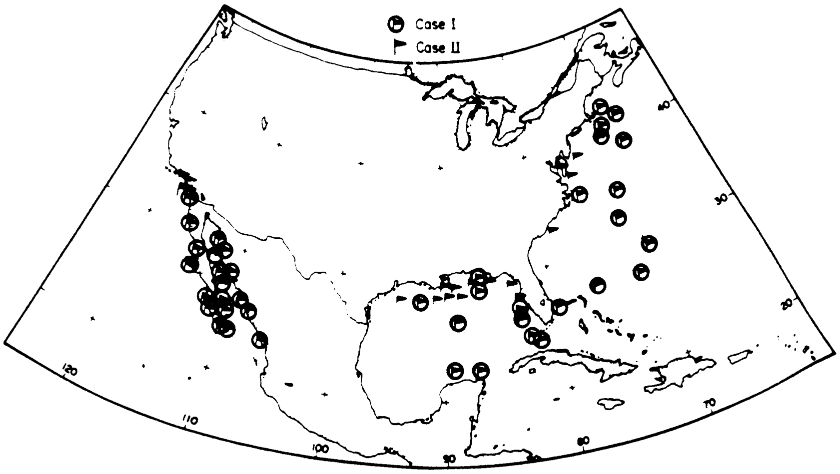


Fig. 1. NET cruise station locations (Gordon et al. 1983a). Case 1 waters are those where the reflectance is dominated by pigment absorption and all other water masses are classified as Case 2.

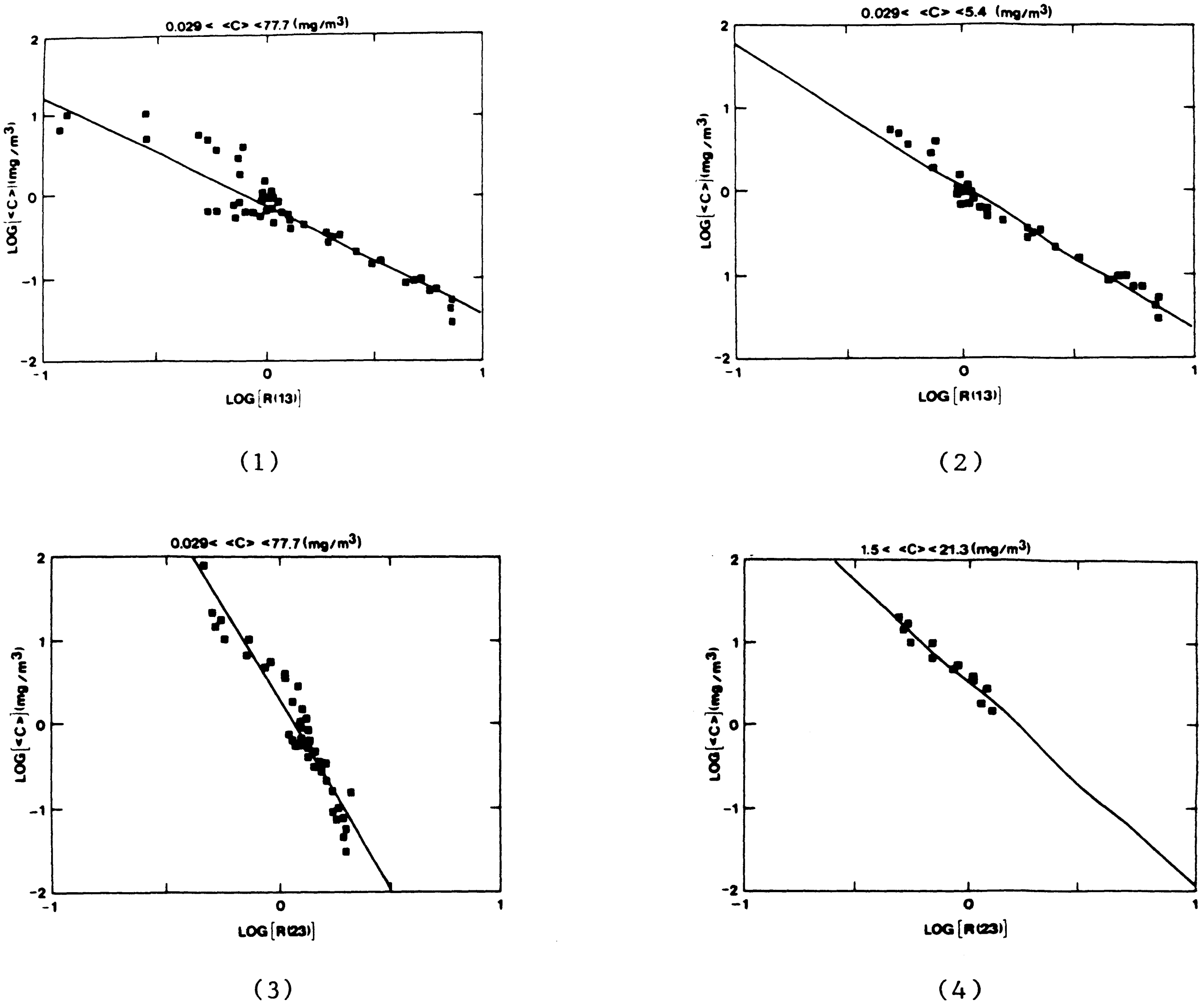
don et al. 1988). The observations for the bio-optical algorithms were collected during a series of Nimbus Experiment Team (NET) pre- and post-launch dedicated cruises off southern California, Baja (Mexico), the Gulf of Mexico, and the East Coast of the United States. (Clark et al. 1980, Austin 1980, and Gordon et al. 1980) as shown in Fig. 1. The observation data sets collected during the cruises included chlorophyll *a* and phaeophytin concentrations, total suspended particulate matter concentration, atmospheric solar transmission, subsurface upwelled spectral radiance and subsurface downwelled spectral irradiance, and downwelled incident spectral irradiance. The radiance and irradiance measurements were from 400–700 nm at 5 nm increments with half power bandwidths of 4 nm.

Two water quality derived products were included in the level-2 processing, pigment concentration and the diffuse attenuation coefficient (K) at 490 nm ($K(490)$). Both were based on ratios of water-leaving radiances. The final pigment concentration algorithm was based on a total of 49 data points for both Case 1 and Case 2 waters (Fig. 2). Case 1 water is defined to be that where reflectance is determined solely by absorption (Morel and Prieur 1977) while the reflectance of Case 2 water is significantly influenced by scattering. The final ($K(490)$) algorithm was derived from 88 data points (Fig. 3). After the first year of the mission, the NET field program was discontinued.

The removal of the atmospheric components (Rayleigh and aerosol radiances) from the total observed radiance is required to derive the estimates of water-leaving radiance as shown in Fig. 4 (NET CZCS algorithm). Successful accomplishment of this correction is essential, and, in general, is not straightforward for any remote sensing application. The problem lies in closure of the system of radiance equations because there are many more unknowns than there are quantities measured or theoretically computed. In the case of the CZCS, an innovative approach was developed based on two radiometric properties of the ocean, which allows the number of unknowns to be reduced. First, the strong absorption of water in the near-infrared (IR) results in very small water-leaving radiances (L_W) in most open ocean regimes. Second, the normalized water-leaving radiances (L_{WN}) at 520 nm and 550 nm ($L_{WN}(520)$ and $L_{WN}(550)$, respectively) assume fairly constant values in Case 1 waters having concentrations less than about 0.25 mg m^{-3}, so-called "clear water" (Gordon and Clark 1981).

The normalized water-leaving radiances are water-leaving radiances corrected to correspond to a solar zenith angle of zero. By assuming the water-leaving radiance at 670 nm is zero and that portions of a scene are clear water regions, Gordon et al. (1983a) were able to estimate the aerosol radiances at 443, 520, 550, and 670 nm. The method assumes the three Ångström exponents needed to relate the aerosol radiance at 670 nm to the aerosol radiances at the other visible bands have constant values over the entire scene. Also, the approach assumes the aerosol radiances are highly correlated and the aerosol radiance value at 670 nm can be used to estimate the aerosol radiance at 443 nm.

The assumptions in the Gordon et al. (1983a) algorithm present some problems in Case 2 waters where the water-leaving radiance at 670 nm is significantly different from zero, e.g., sediment laden waters and coccolithophore blooms. While the 750 nm band might have been better for the aerosol correction, this band was designed for flagging land and clouds and did not have the sensitivity required for quantifying aerosol radiance. Also, in many situations, the aerosols within a scene are not homogeneous but rather



(1) (2)

(3) (4)

	$R(ij)$	Case	C-range[a]	log$A$	$-B$	r^2	s	N
1	$R(13)$	1 + 2	0.029–77.7	−0.116	1.33	0.91	0.223	55
2	$R(13)$	1	0.029–5.4	+0.053	1.71	0.96	0.130	35
3	$R(23)$	1 + 2	0.029–77.7	+0.229	4.45	0.91	0.218	55
4	$R(23)$	1 + 2	1.5–21.3	+0.522	2.44	0.93	0.098	14

[a] C is in mg/m^3.

Fig. 2. NET pigment algorithm plots and algorithm switching criteria (Gordon et al. 1983a).

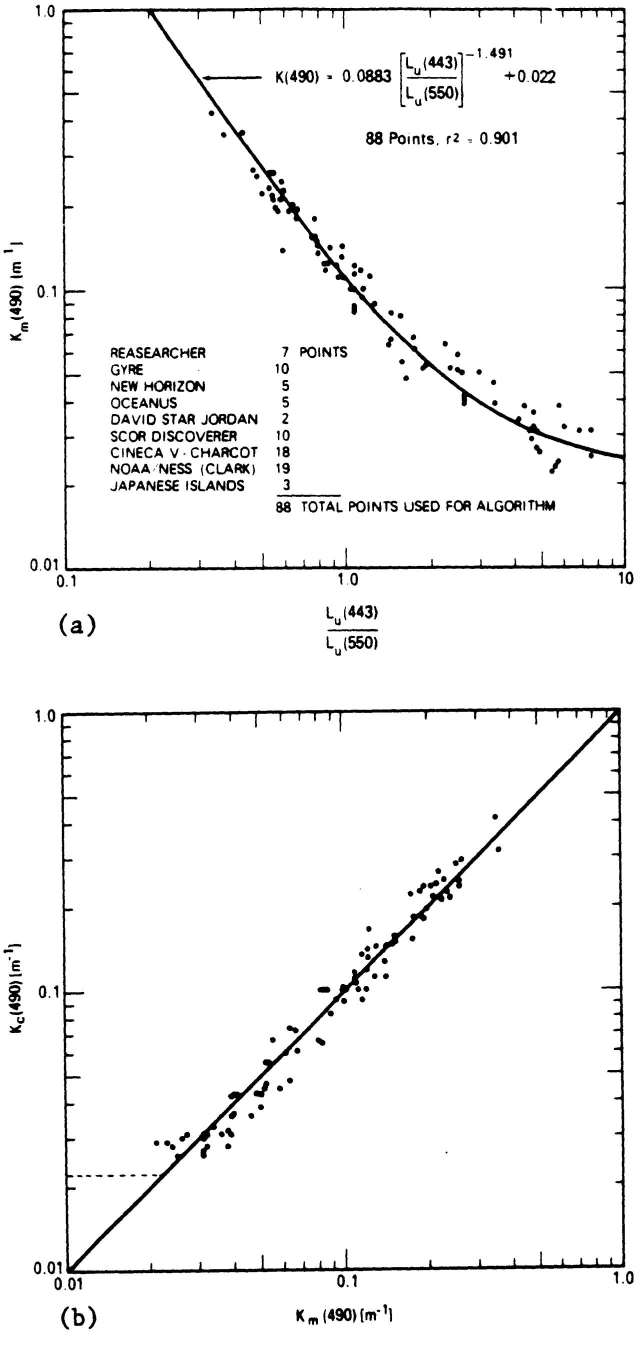


Fig. 3. NET K(490) algorithm plots, **a)** derived relationship between K(490) and the ratio of the inherent upwelling radiance the ocean surface (solid line) together with the database (88 points) and **b)** regression of calculated values of K(490) against the measured values (Austin and Petzold, 1981).

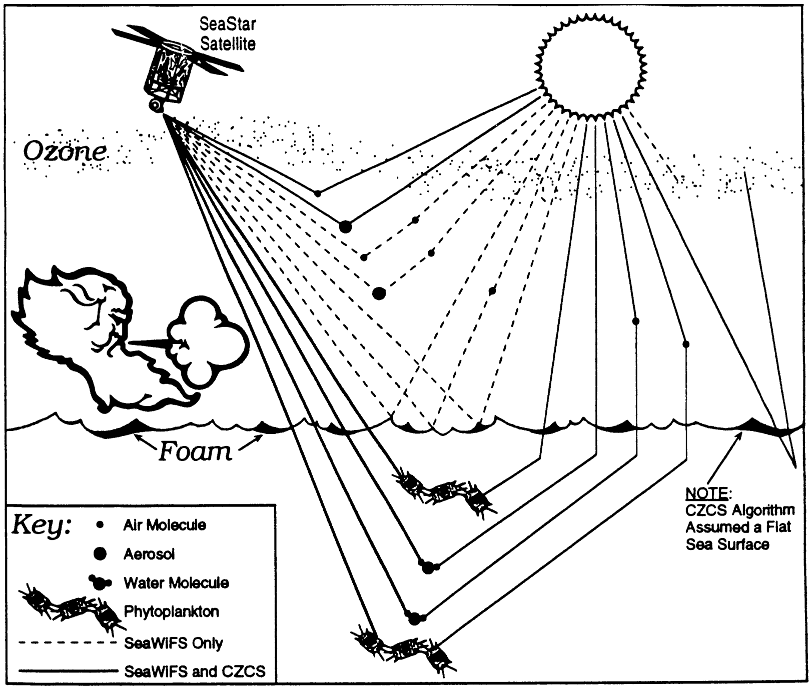


Fig. 4. Schematic of the CZCS and SeaWiFS atmospheric correction algorithms. The elements used in the global CZCS model are shown as solid lines. The dashed lines refer to the new elements to be incorporated into the SeaWiFS model.

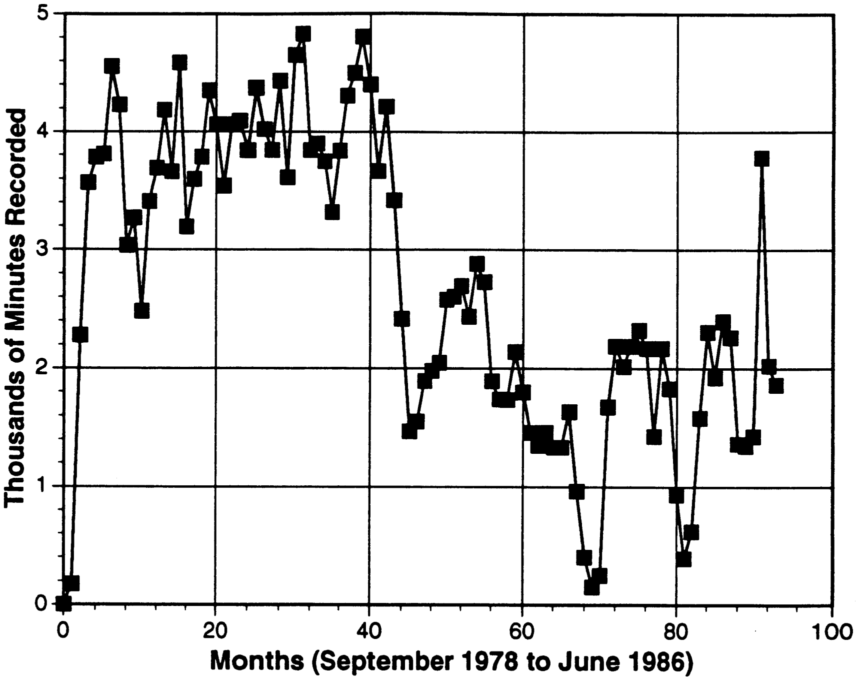


Fig. 5. Monthly total CZCS data collection.

are a mix of continental haze, marine haze, and dust, each having different absorption and scattering properties and different Ångström exponents. While the assumptions in the correction algorithm are not strictly valid in such situations, the technique does produce reasonable results in the majority of cases.

Despite the limited design lifetime of the CZCS mission, data were collected until June 1986. Fig. 5 shows the volume of data collection by the CZCS. The original volume of CZCS data (roughly 250,000 minutes of data or 125,000 two minute scenes) was reduced substantially by screening the level-0 data for cloud cover, so that only reasonably clear scenes were converted to calibrated radiance tapes (CRT, level-1). The screening was performed by the CZCS Project Scientist, Warren Hovis, shortly after the data were received. Even then, the data set filled over 30,000 1600 bpi CRT's with a final volume of approximately 700 Gbytes. The data were partitioned into scenes, usually two minutes (970 scan lines) in length.

In 1985, the NASA/Goddard Space Flight Center (GSFC) and the University of Miami undertook the task of processing all of the CZCS data (Esaias et al. 1986 and Feldman et al. 1989). A major component of the global processing was the duplication of data from tape to write-once-read-many (WORM) optical disks which provide much greater data accessibility and media stability than magnetic tape. The processing included the creation of geophysical products in scanner coordinates (level-2) and average geophysical fields on a uniform global grid (level-3). There were three other major components to the global processing effort: sensor calibration, quality control of the level-2 products, and development of an archive and distribution system. The archive is described in Feldman et al. (1989).

The task of processing the entire data set was complicated by the time-dependent degradation of the sensor's sensitivity. It was determined early in the mission that sensor sensitivity was degrading with time, but quantification of the degradation was difficult to estimate (Viollier 1982, Gordon et al. 1983b, Hovis et al. 1985, Mueller 1985, and Gordon 1987). Because of the relatively large atmospheric contribution to the total observed radiances (Gordon 1981) and the great sensitivity of the bio-optical algorithms to the estimated water-leaving radiances (Clark 1981), small errors in the calibration can induce sizable errors in the derived geophysical products, thereby rendering them useless for many applications. Thus, a comprehensive investigation of the calibration over the entire period of sensor operation was required.

By processing large quantities of clear water imagery, Evans (pers. comm.) was able to develop a vicarious calibration that was used in the global processing of the entire CZCS data set. However, the approach required assumptions that may limit the science that can be performed with SeaWiFS. Specifically, $L_{WN}(520)$ and $L_{WN}(550)$ were assumed to be 0.48 and 0.30 mW cm^{-2} μm^{-1} sr^{-1}, respectively, the Ångström exponents were assumed to be zero, and certain geographical regions such as the Sargasso Sea were assumed be clear water sites (pigment concentrations less than 0.25 mg m^{-3}) at all times. Under these assumptions, analyses of the derived normalized water-leaving radiances indicated what calibration adjustments were required to produce the nominal clear water normalized radiance values. The vicarious calibration of the 443 nm band is tenuous because of the great variability in $L_{WN}(443)$ even in clear water. Additionally, certain command and engineering data from the Nimbus-7 platform were not archived so that a detailed analysis of possible effects related to the spacecraft environment and operation on the sensor's performance and calibration could not be performed. Fig. 6 shows some of the results of the vicarious calibration for the CZCS (Evans unpub.).

The quality control of the level-2 products was performed at GSFC's Laboratory for Oceans (presently named the Laboratory for Hydrospheric Processes), though some scenes were automatically rejected during tape ingest for particular problems, e.g., missing bands. The level-2 processing also employed a land and cloud mask based on a fixed value of band 5 counts and a sensor ringing mask. Sensor ringing occurs on the downscan side of bright targets i.e., clouds and highly reflective land masses and results in invalid total radiances and derived products (Mueller 1988). Software was incorporated in the University of Miami DSP system (a software package for satellite data visualization and processing) which allowed an interactive quality control by the processing team. The procedure simultaneously displayed the daily global composites of pigment, $L_{WN}(443)$, $L_{WN}(550)$, and $L_A(670)$ and allowed for sequencing through each daily mosaic of scenes with the cursor. Thus, each scene was either accepted or rejected and, if rejected, one of nine rejection criteria was selected with optional comments by the investigator.

The six most important categories of scene rejection, in decreasing order, were: duplicate scenes, "dubious" normalized radiances, low sun elevation, no useful data, sun glint contamination, and high $L_A(670)$. Of nearly 62,000 scenes reviewed, over 9,000 were rejected. Fig. 7 presents the distribution of rejections by year and category. The duplicate scenes were due to the creation of multiple copies of the CRTs, which were kept by the Nimbus Project in the tape archive. Most scenes rejected for "dubious" normalized radiance had large areas where $L_{WN}(550)$ was less than half the nominal value of 0.30 mW cm^{-2} μm^{-1} sr^{-1} that were not clearly the result of sun glint or atmospheric dust. (Sun glint and dust both produce high $L_A(670)$ values.) Sun glint can be distinguished from dust because of the consistent pattern it produces in the center of equatorial scenes. A sun glint mask was applied in the level-2 processing, but the mask did not always cover the entire area of contamination because the sun glint pattern is wind speed dependent and the mask algorithm used a constant 6 m s^{-1} wind.

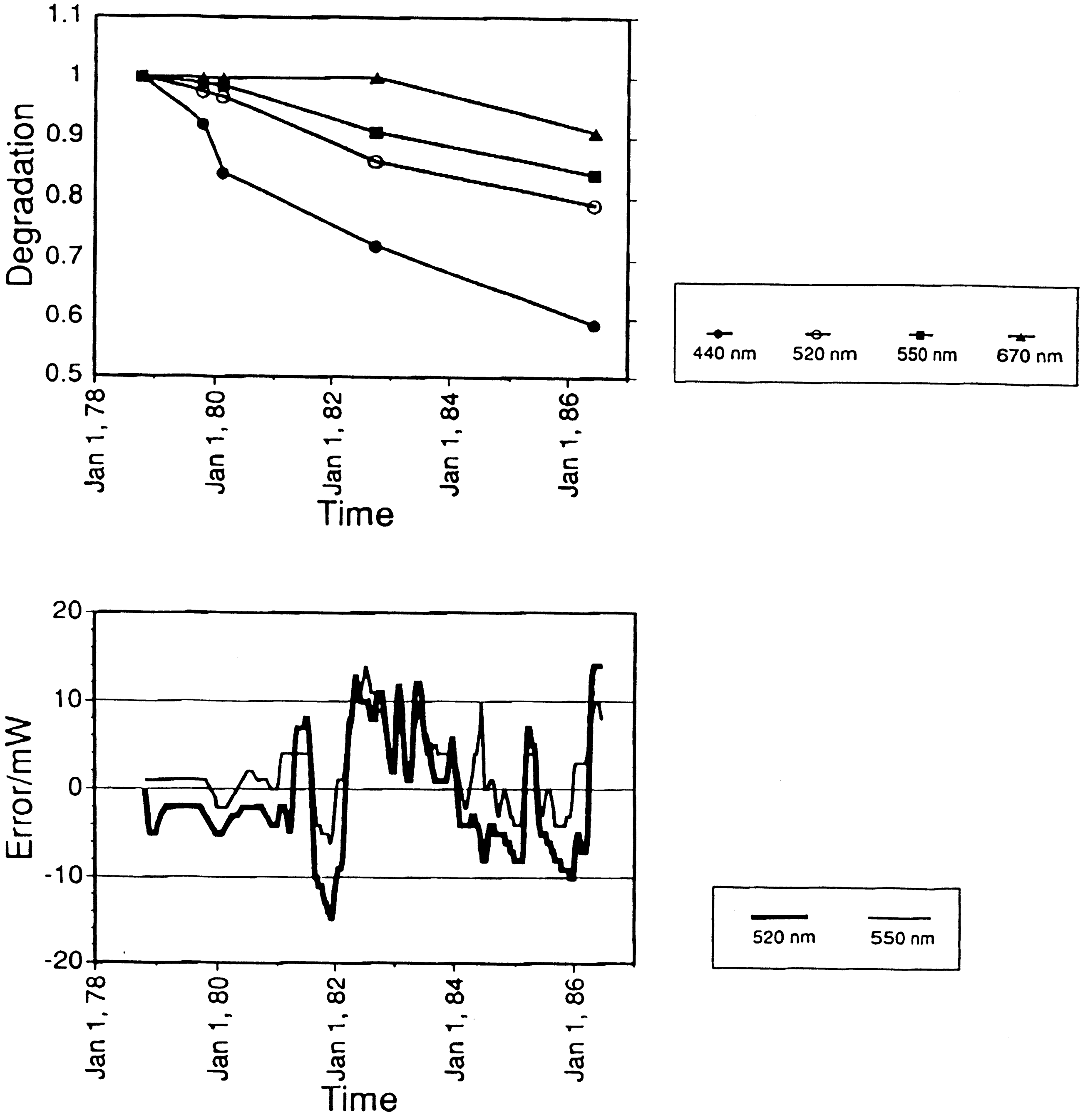


Fig. 6. Vicarious calibration results for the CZCS (unpublished data from R. Evans). On the top is the long-term sensitivity degradation functions of the four visible bands. These functions were used in the global CZCS processing. On the bottom are estimates of the high frequency variability in the calibration of the 520 nm and 550 nm bands.

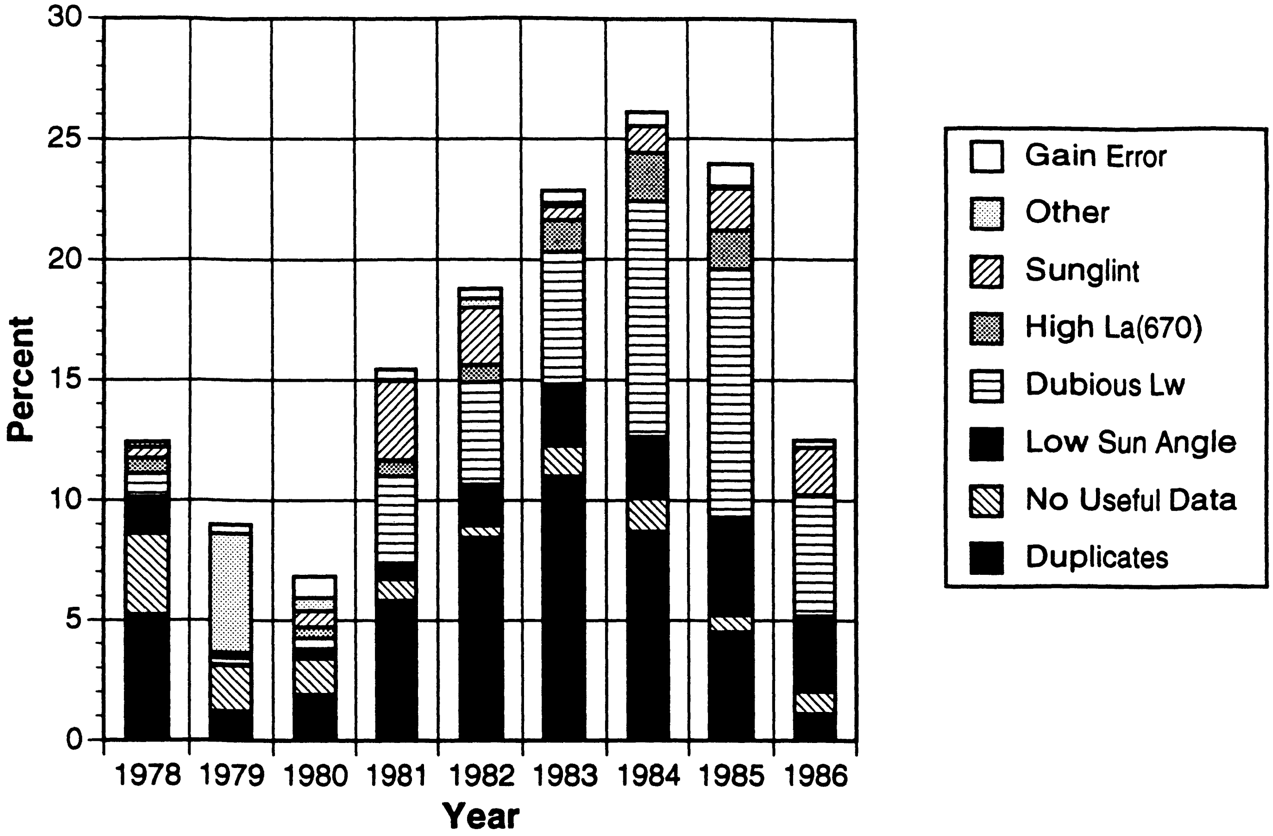


Fig. 7. CZCS quality control results.

The "no useful data" classification was used when a scene was over land or completely cloud covered. Finally, scenes where the solar zenith angle was greater than about 60° were rejected as "low sun elevation" because Fresnel reflectivity for the direct solar radiation increases rapidly as the zenith angle increases beyond 60°. Thus, at large solar zenith angles, the amount of light entering the water column is relatively small as are the upwelling water radiances. Also, errors in the atmospheric correction are expected to be greatest at high zenith angles. The net result was these scenes almost always had very high pigment concentrations which were considered to be erroneous.

The global CZCS data processing was completed in March 1990, and provided a glimpse of the global distribution of total pigment concentration (Fig. 8) and $K(490)$ even though its coverage was sparse (Fig. 9). Clearly, the mission exceeded the original goals, but the data set does not clearly resolve the seasonal cycle and interannual variability on global scales. Recent reviews of the science derived from the CZCS data set are found in Abbott and Chelton (1991) and McClain et al. (1991a) with the latter also providing an overview of the quality control procedures used in the CZCS global processing.

Much was learned from the CZCS experience in terms of calibration requirements, sensor design, algorithm design, and scientific applications. SeaWiFS is designed to compensate for a number of shortcomings in the CZCS data set. The CZCS band selection did not allow the separation of photosynthetically viable chlorophyll a from degradation products. The inclusion of the 410 nm band in SeaWiFS should help separate these pigments. Also, it is expected that the bio-optical algorithms will be improved based on the development of more comprehensive bio-optical data sets and that algorithm problems such as those noted by Denman and Abbott (1988) and Muller-Karger et al. (1990) will be eliminated. The design of the near-IR band precluded its use for atmospheric corrections in turbid waters. SeaWiFS will have bands at 765 nm and 865 nm.

The CZCS internal calibration via calibration lamps

Fig. 8. Global pigment composite containing all the CZCS data processed and accepted during the quality control.

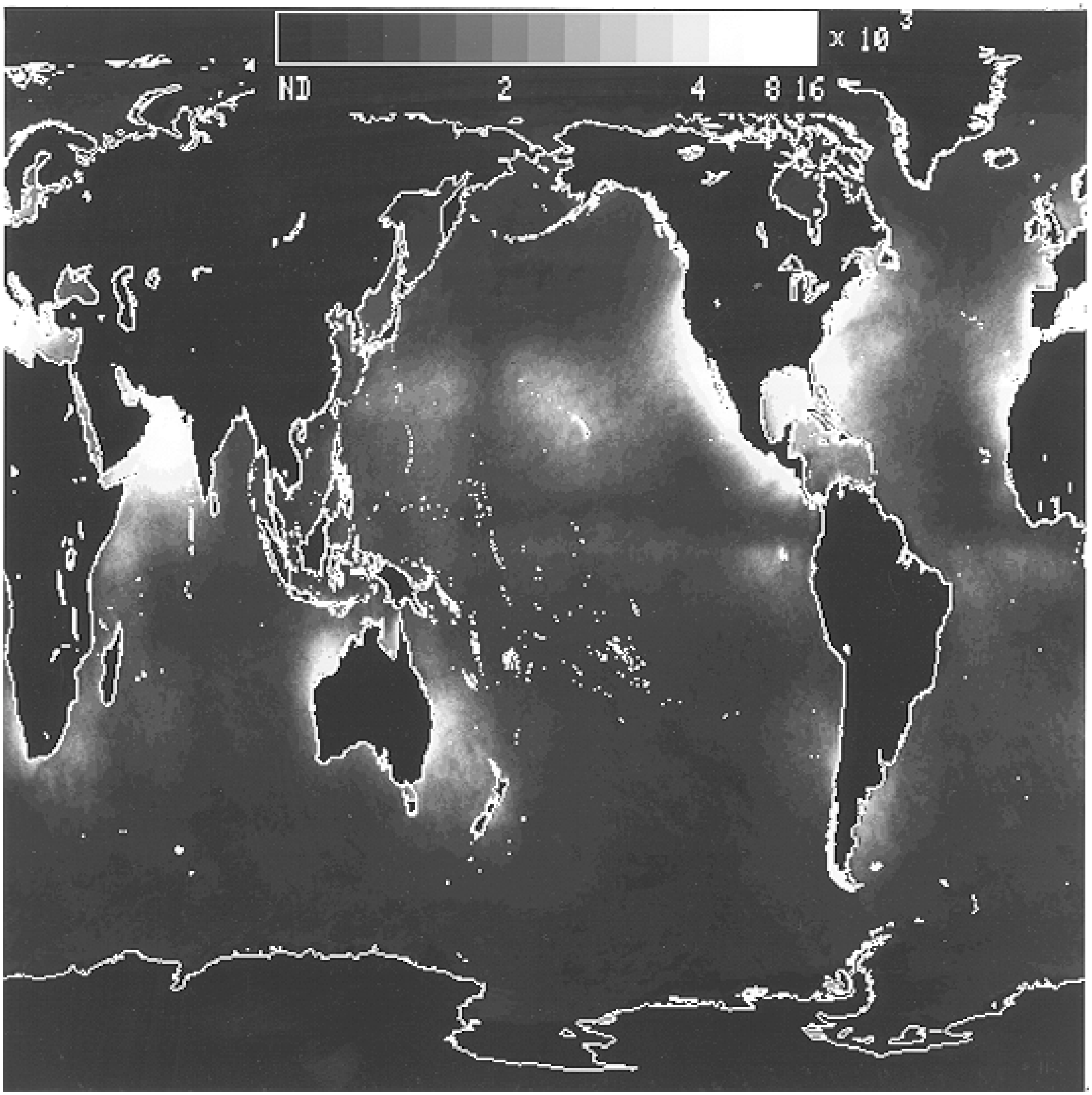


Fig. 9. Global sampling from CZCS for total 92-month operation (11/78–6/86). Note that the global processing subsampled the original level-1 data by one-sixteenth.

was unreliable. This limitation required the application of a vicarious calibration technique based on nominal values of $L_{WN}(443)$, $L_{WN}(520)$, and $L_{WN}(550)$ which proved to be reasonably correct for some periods, but only marginally correct for others (Balch et al. 1991 and Hay et al. 1991). SeaWiFS will use imagery of the moon, data from a solar illuminated diffuser plate, and a mission-long field program to track the sensor performance. Finally, the instrument signal-to-noise ratios (SNR) are vastly improved which, coupled with 10-bit digitization, will allow more highly resolved quantification of radiances and derived products. Tables 1 and 2 provide the CZCS and SeaWiFS performance specifications, respectively.

Table 2. Major instrument parameters and characteristics of the SeaWiFS ocean color instrument.

Instrument Bands				
Band	Wavelength FWHM [nm]	Saturation Radiance[1]	Input Radiance[1]	SNR[2]
1	402–422	13.63	9.10	499
2	433–453	13.25	8.41	674
3	480–500	10.50	6.56	667
4	500–520	9.08	5.44	616
5	545–565	7.44	4.45	581
6	660–680	4.20	2.60	447
7	745–785	3.00	1.61	455
8	845–885	2.13	1.09	467

Sensor Accuracy	
Radiance Accuracy:	<5% absolute each band
Band Registration:	<0.3 pixel
Location Knowledge:	<1 pixel
Saturation Recovery:	<10 pixels (7 estimated)
Polarization:	<2% (<1% expected)
Nadir Resolution:	1.1 km LAC; 4.5 km GAC

Mission Characteristics	
Orbit Type:	Sun Synchronous at 705 km
Equator Crossing:	Noon ±20 min., descending
Duty Cycle:	100% daylight
Swath Width (at equator):	2,800 km LAC (±58.3°) 1,502 km GAC (±45.0°)
Scan Plane Tilt:	+20°, 0°, −20°
Dynamic Range:	10 bits quantization; 4 gains

1. Units of mW cm^{-2} μm^{-1} sr^{-1}; gain 1.
2. Measured at input radiances.

1.2 Future Perspective

SeaWiFS will be the first in a sequence of ocean color related missions (Fig. 10) that include Japan's ADEOS Ocean Color Temperature Sensor (OCTS) and the EOS MODIS-N. Tables 3 and 4 provide the sensor specifications for OCTS and MODIS-N, respectively. Other missions at various stages of planning and development are Germany's Reflective Optics System Imaging Spectrometer (ROSIS), the European Space Agency's Medium Resolution Imaging Spectrometer (MERIS), and Japan's Global Imager (GLI). Thus, SeaWiFS will initiate a continuous global time series of ocean color data that should extend well into the next century. Because SeaWiFS will have a design lifetime of at least 5 years, it is likely to be operational when OCTS and MODIS are launched.

Table 3. Major instrument parameters and characteristics of the OCTS satellite.

Instrument Parameters					
Band	Wavelength[1]	Bandwidth[1]	Radiance Gain		Sensitivity[2]
			Normal	Low	
1	0.412	0.020	145	97	0.095
2	0.443	0.020	150	100	0.098
3	0.490	0.020	130	87	0.085
4	0.520	0.020	120	80	0.078
5	0.565	0.020	90	60	0.0586
6	0.665	0.020	60	40	0.0391
7	0.765	0.040	40	27	0.0264
8	0.865	0.040	20	13	0.0127
9	3.70	0.30			
10	8.50	0.50			
11	11.0	1.0			
12	12.0	1.0			

Instrument Characteristics	
SNR Performance:	Bands 1 and 8, 450 Bands 2–7, 500
NEΔT (at 300° K):	Bands 9–11, 0.15° K Band 12, 0.20° K
Scan Angle:	±45°
Swath Width:	1,400 km
Tilt Angle:	±20°
Polarization Sensitivity:	Band 1, 5% Bands 2–8, 2%
Digitization:	10 bits
Design Life:	3 years

Instrument Calibration	
VISNIR, Type:	Deep Space (each scan) Sunlight (once a day) Lamp (once a week)
VISNIR, Accuracy:	±10% abs. (each band) ±3% rel. (band-to-band)
IR, Type:	Deep Space and Black Body (each scan)
IR, Accuracy:	±0.4° K at 300° K

1. Units of μm.
2. Ten bits, high gain, in units of rad./count.

In order for the data from these missions to be useful for quantifying long-term trends in oceanic biological processes, comprehensive and consistent calibration and algorithm validation programs are needed for each mission. These programs must include product and calibration comparisons when missions overlap in time, since the instruments will not be identical, in terms of their radiometric characteristics, and the derived products from each will be based on sensor specific algorithms. Therefore, care must be taken to ensure that the algorithms, both atmos-

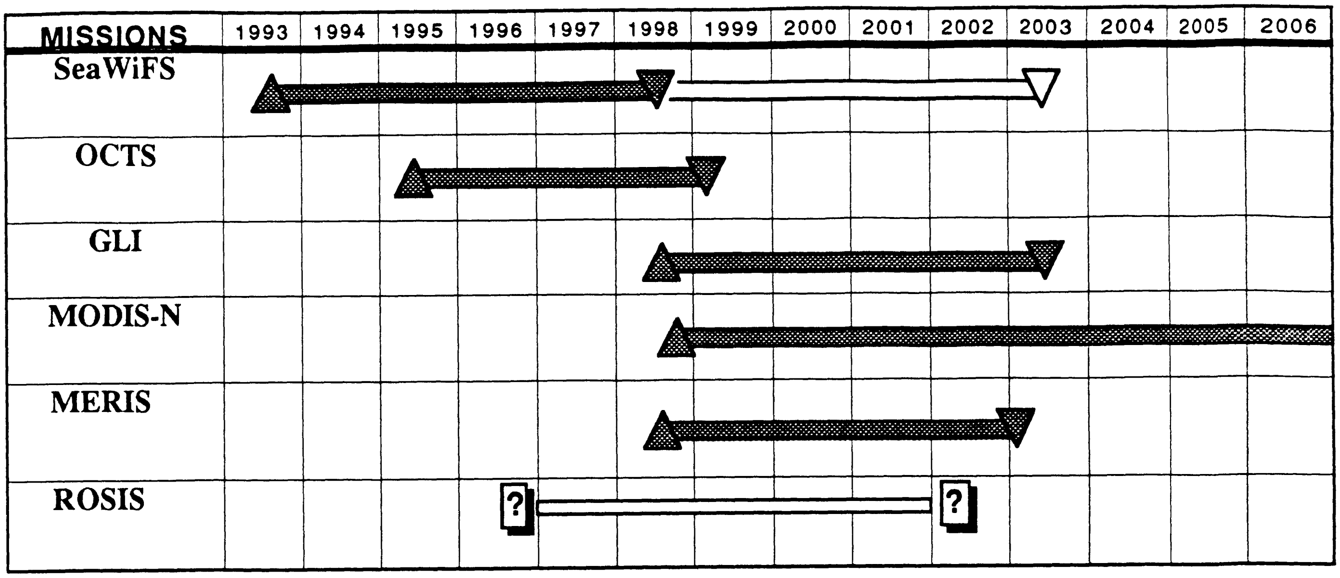


Fig. 10. Ocean color mission launch and operation schedule.

pheric and bio-optical, produce reasonably similar derived products. The techniques developed for calibration and atmospheric and bio-optical algorithm development for SeaWiFS will provide the baseline for subsequent ocean color missions.

Table 4. Major instrument parameters and characteristics of the MODIS-N sensor.

Sensor Accuracy	
Polarization:	2% max., <2.2 μm
IFOV (Number of bands @ IFOV):	29 @ 1,000 m 5 @ 500 m 2 @ 250 m
Spectral Bands:	36, 19 @ 0.4– 3.0 μm 17 @ 3.0–15.0 μm (10–500 nm width)
Radiometric Accuracy:	5% absolute, <3 μm 1% absolute, >3 μm 2% reflectance
NEΔT (at 300° K):	<0.05
Mission Characteristics	
Orbit Type:	Sun Synch., 705 km
Swath Width:	110°, 2,330 km
Average Data Rate:	11.0 Mbps (day) 1.8 Mbps (night)
Dynamic Range:	12 bits quantization
Duty Cycle:	100%

1.3 Science Mission Goals

The design of SeaWiFS was driven by science requirements as defined by the SeaWiFS Prelaunch Science Working Group (SPSWG). The SPSWG was an ad hoc committee selected by NASA Headquarters for the purpose of providing to NASA guidance in the formulation of mission objectives, specifications, and goals. Table 5 is a list of the membership. This group was dissolved prior to the release of the NASA Research Announcement (NRA) for SeaWiFS. A new Science Working Group (SWG) will include those individuals selected for funding under the NRA. The science requirements have been refined over the past 10 years, as documented in *The Marine Resources Experiment (MAREX) Program Report* (NASA 1982), and a NASA/Earth Observation Satellite Company (EOSAT) report written by the Joint EOSAT/NASA SeaWiFS Working Group in 1987. The SeaWiFS science mission goals are the following:

1) Determine the magnitude and variability of the annual cycle of global oceanic primary production.
2) Quantitatively assess the ocean's role in the global carbon cycle and other biogeochemical cycles.
3) Quantify the relationships between ocean physics and large scale patterns of productivity.
4) Determine the spatial and temporal distributions of phytoplankton blooms.
5) Advance the scientific applications of ocean color data and the technical capabilities required for data processing, management, and analysis in preparation for future missions.

Given these scientific objectives, the specific set of observational specifications are the following:

1) Radiometric accuracy to within 5% absolute and 1% relative.
2) Derivation of water-leaving radiances to within 5% absolute.
3) Derivation of chlorophyll *a* concentration to within 35% over the range 0.05–50.0 mg m^{-3}.
4) Derivation of global primary production to within 50% absolute with a precision to within 10%.

These are rather stringent requirements and necessitate calibration verification and algorithm development programs that are far more comprehensive than were undertaken for the CZCS or even envisioned in earlier CZCS follow-on studies.

1.4 Sensor Characteristics

SeaWiFS differs from the CZCS in a number of ways (compare Tables 1 and 2). It has 6 (412, 443, 490, 510, 555, and 670 nm) rather than 3 (443, 520, and 550 nm) bands for pigment concentration algorithms. Two additional bands in the near-IR (765 and 865 nm) are for quantification of aerosol radiances. It employs a rotating telescope to reduce polarization sensitivity inherent in the scan mirror design of the CZCS. The digitization is 10 bits rather than 8. SeaWiFS has a strict requirement on sensor ringing that requires the effect (bright object recovery) to be dampened out within 10 pixels. Also, SeaWiFS will have a scan of 53.8° from nadir, as opposed to 39° for the CZCS. Only the ±45° portion of the scan will be used to produce the global data set at GSFC. In order to utilize data at scan angles greater than 39°, more accurate atmospheric correction algorithms will be needed than were used for the CZCS processing.

Finally, SeaWiFS onboard calibration will employ a solar diffuser plate and lunar imaging during scheduled platform maneuvers rather than using internal calibration lamps which proved inadequate on the CZCS. These onboard calibrations are possible because Gains 1 and 2 (Appendix A) have been designed specifically for these applications. Gains 3 and 4 will be used during normal Earth viewing operations. Gains set the dynamic range of the instrument and allow the range to be matched to the expected magnitude of the total radiance at each wavelength. This provides a mechanism for optimizing the quantification of the radiance.

1.5 Program Structure

The calibration and validation program is made up of three general components: the calibration of the SeaWiFS instrument, the development and validation of the operational atmospheric correction algorithm, and the development and validation of the derived product algorithms, e.g., chlorophyll *a* concentration. These activities will be pursued through in-house (internal) tasks and contracts with the outside community (external). The internal activities include all work to be conducted at GSFC by SPO personnel and on-site contractors. The external activities are performed elsewhere and include funding of contracts to other government agencies and academic institutions for specific services, such as *in situ* data collection, mooring deployment, and maintenance. These external activities are necessary because the SPO has neither the skill mix nor the manpower to conduct certain functions.

Both internal and external activities will be discussed in detail later and are separately listed in the budget to clearly show how the work is being partitioned, what levels of funding are being used at GSFC, and what constitutes "pass through" monies from the SeaWiFS Research and Technology Operation Plan (RTOP). Figures 11 and 12 provide overview schematics of the Calibration and Validation Program structure and milestones, respectively. Elements of these charts will be discussed in separate sections below.

Figure 13 shows the overall organization of the SPO (Code 970.2) at NASA/GSFC. The sensor calibration and validation effort requires close coordination between the Instrument Scientist (Dr. William Barnes, Code 970), the Calibration Manager (Dr. Bruce Guenther, Code 920.1), the SeaWiFS Project Scientist (Dr. Wayne Esaias, Code 971), the Algorithm and Validation Manager (Dr. Charles McClain, Code 971), and Code 930 personnel will handle the routine data reception, processing, and operations management. The composition of the SPO straddles organizational boundaries and reflects the fact that SeaWiFS is an Earth Sciences Directorate (Code 900) activity.

The internal activities related to calibration can further be divided into those associated with the onboard calibration (W. Barnes and B. Guenther) and those connected with the vicarious calibration (C. McClain). The onboard calibration is made up of analysis and documentation of the initial prelaunch characterization and calibration data provided by the Hughes/Santa Barbara Research Center (SBRC) and the analysis of post launch data from the solar diffuser plate and lunar imagery. The vicarious calibration involves the collection, analysis, and comparison of optical surface truth with the derived satellite water-leaving radiance fields. A separate calibration activity involving aircraft will be coordinated with the MODIS calibration program (Bruce Guenther and Peter Abel) as discussed below.

Included in the validation program is the development of the atmospheric correction and bio-optical algorithms required to produce the derived products as defined by the SPSWG. Presently, the atmospheric correction algorithms needed for processing SeaWiFS data have not been developed and a number of improvements over the CZCS algorithms are necessary; however, to implement these improvements, some field studies are required to collect specific data sets. Similarly, because the existing bio-optical

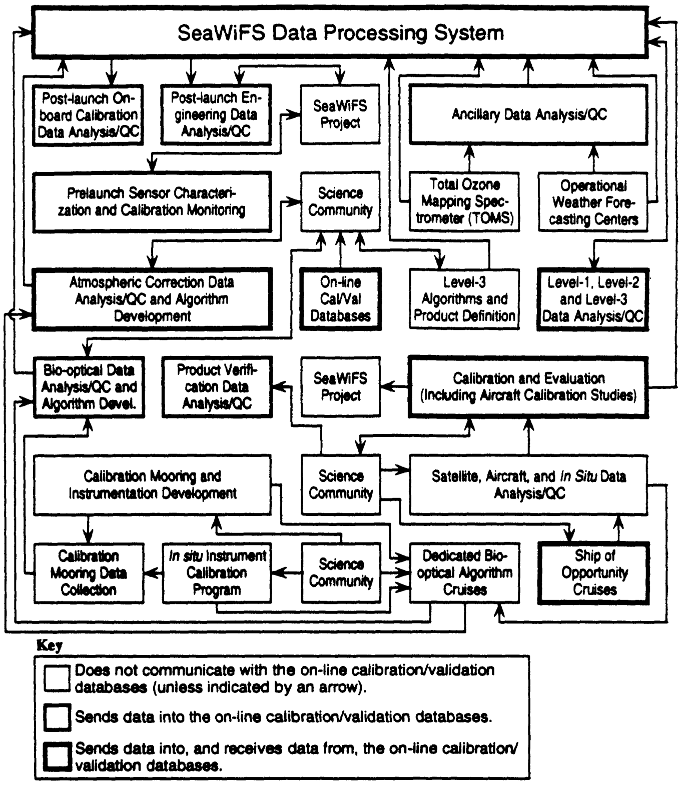


Fig. 11. SeaWiFS Calibration and Validation Program schematic.

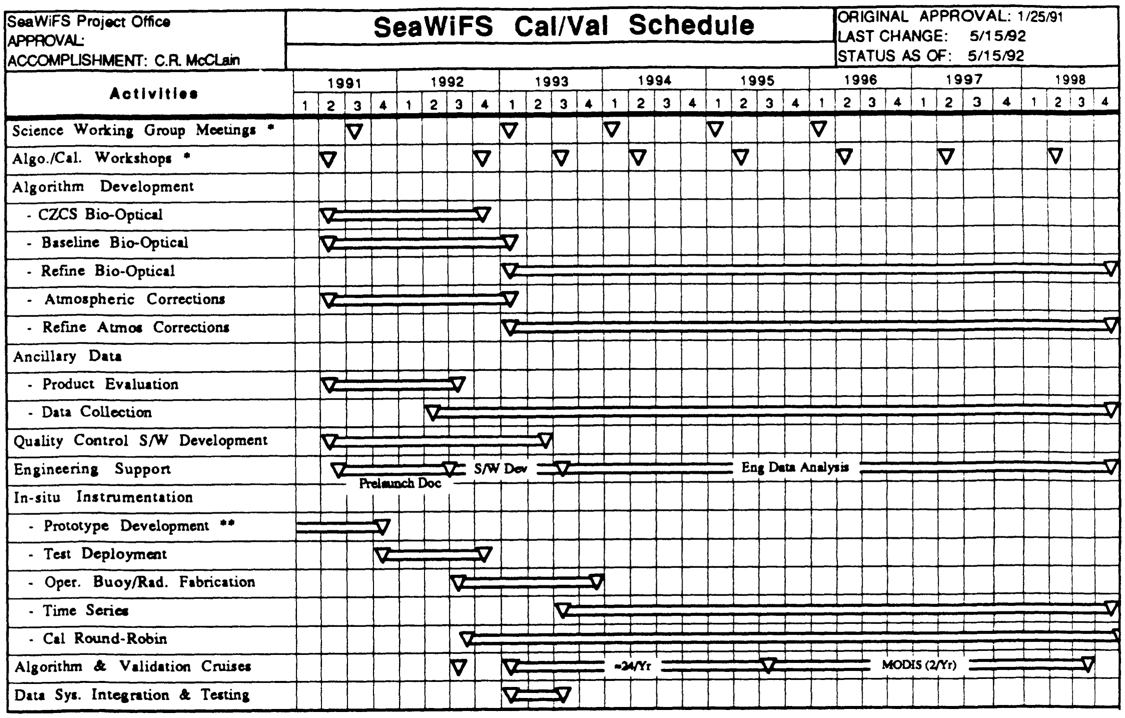


Fig. 12. SeaWiFS Calibration and Validation Program milestones. (Key: * = some SWG and algorithm/calibration workshops may be combined, and ** = prototype development initiated prior to 1991 under separate funding.)

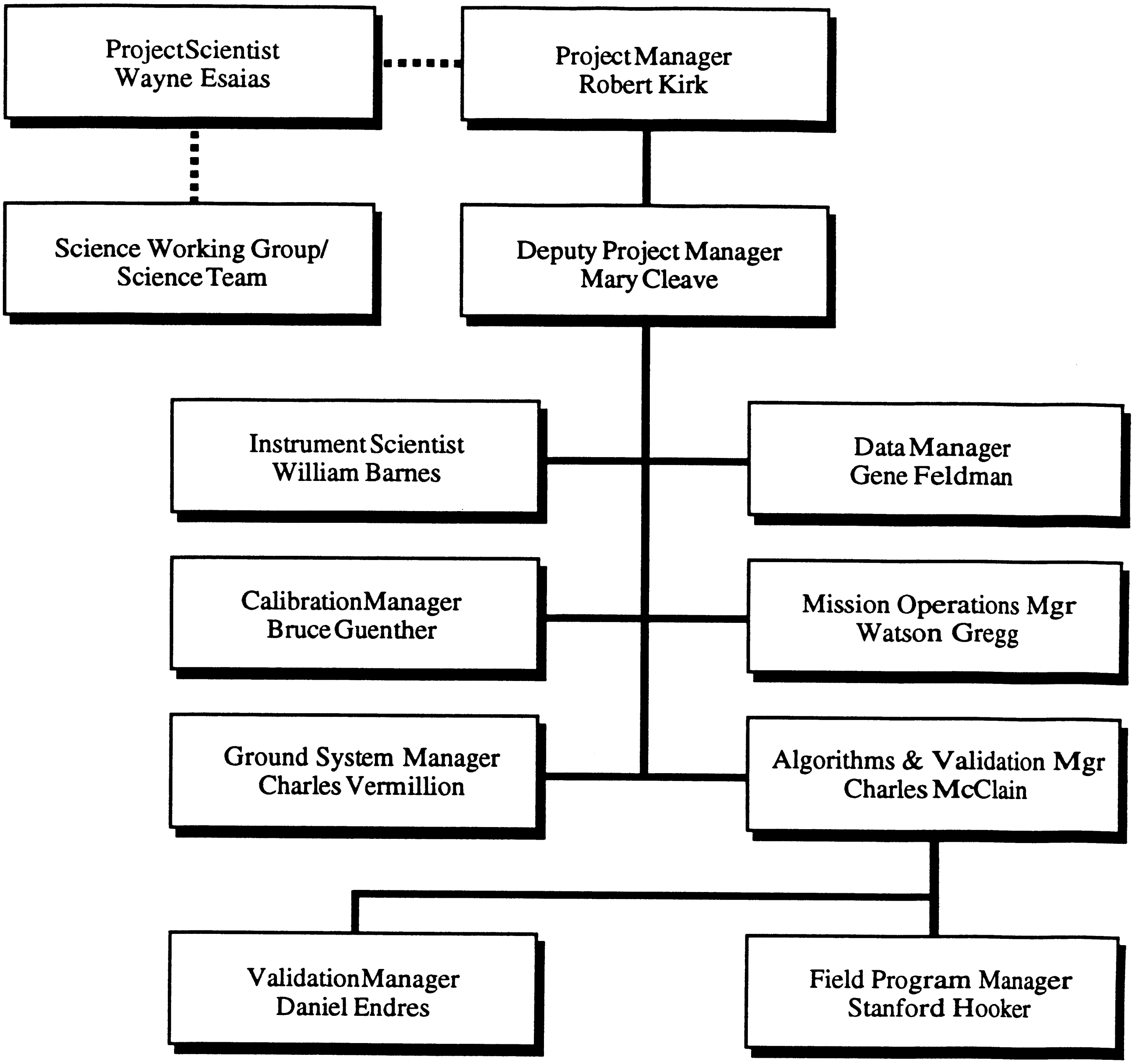


Fig. 13. SeaWiFS Project Organization.

Table 5. Members of the SeaWiFS Prelaunch Science Working Group.

Team Members			
Mark Abbott[2,3]	Oregon State University	Howard Gordon[2]	University of Miami
James Aiken	PMEL, United Kingdom	Graham Harris[3]	CSIRO, Australia
Robert Bidigare	University of Hawaii	Patrick Holligan	United Kingdom
Peter Brewer[3]	MBARI	Marlon Lewis	Dalhousie, Canada
Otis Brown[2]	University of Miami	Satsuki Matsumura	FSFRL, Japan
Janet Campbell	Bigelow Marine Laboratory	Andre Morel	IOS, France
Kenneth Carder[2]	University of South Florida	James Mueller	San Diego State University
Dennis Clark[2]	NOAA	Mary Jane Perry	University of Washington
Peter Cornillon	University of Rhode Island	Trevor Platt	Bedford Institute, Canada
Curtiss Davis	Jet Propulsion Laboratory	James Simpson	Scripps Inst. of Oceanography
Kenneth Denman	IOS, Canada	Raymond Smith	Univ. of Calif. Santa Barbara
Hugh Ducklow	University of Maryland	Charles Trees	San Diego State University
Wayne Esaias[1,2]	NASA/GSFC	John Walsh	University of South Florida
Richard Eppley	Scripps Inst. of Oceanography	James Yoder	University of Rhode Island
Robert Evans[2]	University of Miami		
Ex Officio Members			
Greg Mitchell	NASA Headquarters	Rick Spinrad	Office of Naval Research
Curt Mobley	Office of Naval Research	Stan Wilson	NASA Headquarters
SeaWiFS Project Members			
William Barnes	Instrument Scientist	Bruce Guenther	Calibration Manager
Mary Cleave	Deputy Project Manager	Stanford Hooker	Field Program Manager
Daniel Endres	Asst. Validation Manager	Robert Kirk	Project Manager
Wayne Esaias	Project Scientist	Charles McClain	Algorithm and Validation Mgr.
Gene Feldman	Data Manager	Charles Vermillion	Ground System Manager

1. Chairman of SeaWiFS Prelaunch Science Working Group (SPSWG).
2. MODIS Science Team member (other MODIS Ocean Team members are: F. Hoge, GSFC; J. Parslow, Aus.; and I. Barton, Aus.)
3. EOS Interdisciplinary Investigator.

data sets applicable to SeaWiFS are either very limited in scope or are nonexistent, a field program must be implemented to support dedicated bio-optical cruises. These field studies are in the external activities category, however, some GSFC personnel may participate. Internal activities include the development of bio-optical databases and the comparison of different atmospheric correction and bio-optical algorithms. These databases will be accessible to outside investigators, funded by the SPO, to assist in algorithm development.

General accessibility to the databases by the research community will not be supported because of system security and system resource utilization concerns. Appendix B provides a statement of the data distribution policy as of August 1991, when it was presented to, and accepted by, the SPSWG. These data will be provided to an operational archive such as the GSFC Distributed Active Archive Center (DAAC) at some point in time for distribution. Because the atmospheric correction algorithms utilize data products from other sources, e.g., ozone concentrations, surface wind and pressure fields, some quality control of these fields must be undertaken before the data are incorporated into the processing. Finally, there must be a quality control function for the final derived products that compares them to simultaneous field observations submitted to the SPO by various field programs and individual investigators.

All GSFC internal operations are located with the SeaWiFS processing system and utilize certain common subsystems and databases. This is different from the CZCS processing scenario where calibration functions were undertaken at the University of Miami and the quality control of the derived products was conducted at what is now the Laboratory for Hydrospheric Processes' Oceans Computer Facility. The integrated SeaWiFS arrangement will simplify communication between the calibration and validation group and the operations personnel. Also, it more readily accommodates the demands of near real-time data processing, which was not a consideration in the CZCS processing. The processing system is designed to accommodate the calibration and validation computational and data storage requirements, so that these activities do not impede the operational data processing.

2. CALIBRATION VERIFICATION

SeaWiFS calibration and characterization will consist of three activites: pre-launch, on board, and post-launch.

2.1 Pre-launch Program

Pre-launch calibration and characterization of SeaWiFS will be governed by four documents: 1) *The Spacecraft Product Assurance Plan*, 2) *The Space Segment Verification Plan*, 3) *The Sensor Product Assurance Plan*, and 4) *The Sensor Calibration and Stability Monitoring Plan.* The latter two will be subsets of the first two. A conceptual version of document 4 was a part of the contractor's proposal and included in Fig. 14, an overview of SeaWiFS calibration and characterization activities. Table 6 is a summary of tests and major hardware required to verify SeaWiFS' performance. The six major phases and tasks leading to the delivery of SeaWiFS to the spacecraft are described below:

1. *Subsystem Assembly and Testing:* This phase consists of a) assembly and alignment of the scanner rotating elements and focal beam optics and focus adjustment of the off axis folded telescope; b) assembly, alignment, and focus adjustment of the relay and focal plane optics and static coregistration of all spectral bands; and c) assembly and functional testing of the electronics module, including validation of proper performance over the qualification temperature range and the expected output power voltage variation.

2. *System Assembly, Parameter Adjustment, and Functional Operation Validation:* This phase consists of the following: a) dynamic verification of spectral band coregistration, IFOV size, and optical focus; b) measurement of spectral bandpass parameters; c) adjustment of the transmitting polarization compensator to achive a minimum value of polarization sensitivity over the 45° degree portion of the scan that is to be used for processing to level-2 products; d) measurement and adjustment of the 20° tilt angle position and its operation; e) verification of command execution and telemetry output; f) adjustments of band offset and gain; g) solar calibration throughput and functional operation; h) verification of immunity to the expected spacecraft generated radio frequency environment and conducted interference noise levels; i) power levels and ground isolation measurements; and j) bright target recovery measurements.

3. *Radiometric Calibration:* The calibration will be accomplished using the 122 cm (48 inch) spherical integrating source (SIS), designed by NASA, or its equivalent. At this time, the final spectral band gain trim adjustments will be made, if necessary, in order to comply with the maximum full scale scene radiance requirement.

4. *Initial Baseline Testing and Performance Verification:* In the initial phase, tests will be performed that will provide a benchmark for comparison of all subsequent testing. In particular, data comparisons will be made following each environmental test exposure to detect any change in parameter performance that would indicate a potential problem area. The baseline test will include, as a minimum, a measurement of the following performance parameters: a) polarization sensitivity as a function of scan angle, b) radiometric sensitivity (SNR), c) spectral band coregistration verification, d) single point check of calibration, e) modulation transfer function (MTF) measurements, and f) pixel location characterization. In addition, power level and ground isolation measurements will be made and the functional operation of all command and telemetry channels will be verified. Where feasible, the baseline tests will be automated to provide test uniformity for parameter performance change evaluation.

5. *Environmental Testing:* This phase will involve subjecting the sensor to a) random vibration profile levels that will approximate the expected launch environment and b) test under a thermal vacuum environment. A baseline test will be performed after the vibration exposure and before the thermal vacuum tests to verify that no performance or operational degradation occurred as a result of the vibration exposure. The instrument will be configured in the thermal vacuum chamber so that it will view and scan the SIS through a chamber window. Prior to the start of thermal vacuum exposure, a "calibration transfer" from the basic SIS to the window SIS arrangement will be made using the instrument as the transfer vehicle. The thermal vacuum tests will be designed to test the instrument under a simulated on-orbit temperature and vacuum profile. During the simulated 40% duty cycle, the sensor will scan the SIS, and the recorded spectral band data will be used to characterize the sensor's radiometric calibration as a function of the instrument's temperature in a vacuum environment. In addition, all functional operations will be verified and the thermal response of the sensor will be evaluated as a means of validating the scanner and electronics module thermal nodal model.

6. *Final Baseline Testing and Performance Verification:* A final baseline, post environment test will be performed prior to delivery of the instrument for spacecraft integration. In addition, the SeaWiFS spectral bandpass parameters will again be measured and compared with the initial measurements for parameter stability validation.

GSFC's role during integration and testing will be that of an observer tasked with assuring system compliance with NASA's data requirements. The *Calibration and Stability Monitoring Plan* will require GSFC approval and

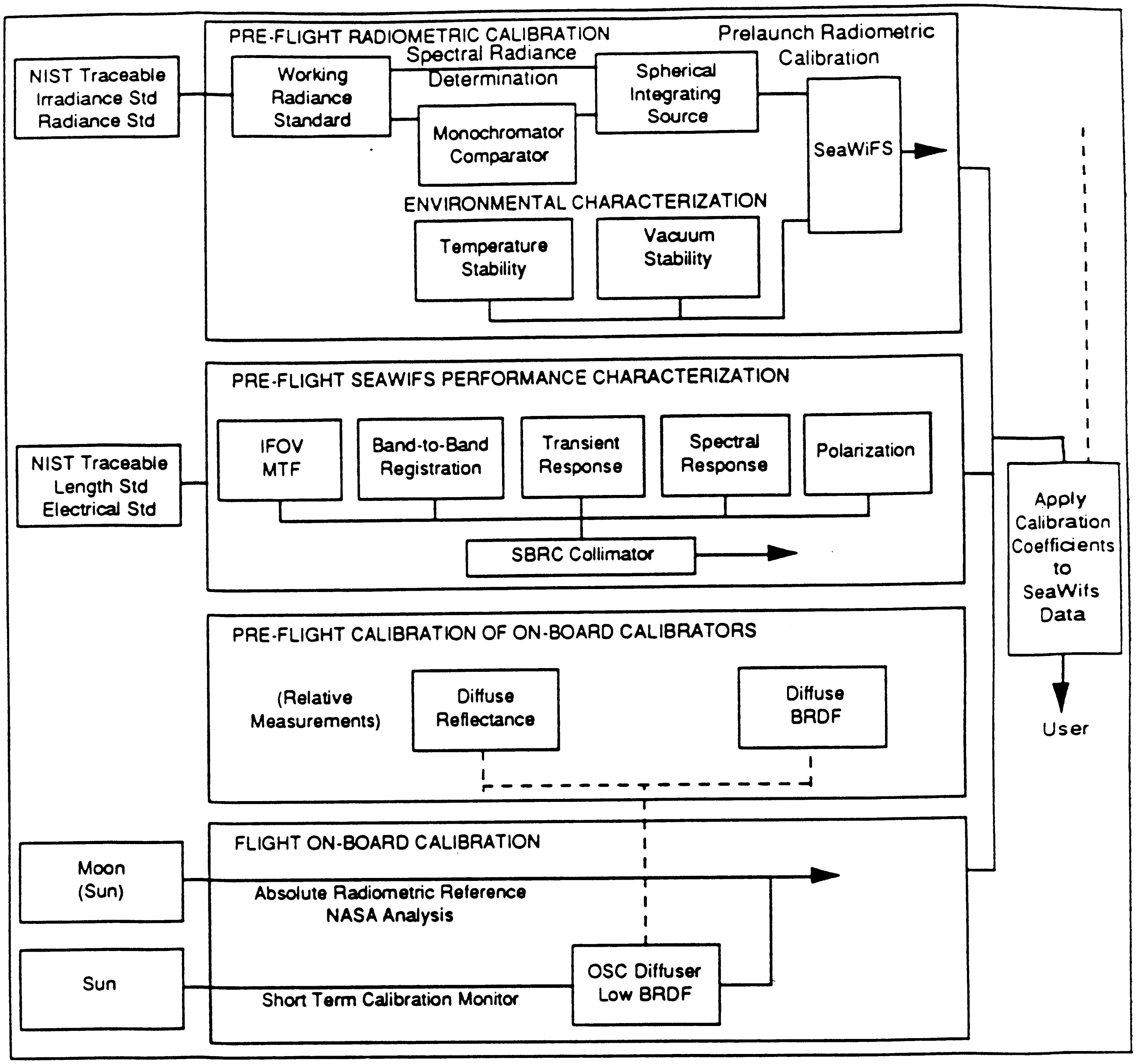


Fig. 14. SeaWiFS instrument calibration and characterization sequence (provided by OSC).

Table 6. SeaWiFS test plan summary.

Requirement	Development Phase for Test/Demo.	Demonstration Shift	Major Test Equipment Required
2.2 Spatial Coverage (IFOV Size) 1 km IFOV ±0.15 km	Ambient Baseline	▪ With SeaWiFS scanning across an illuminated knife edge within collimator, shift collimator to scan IFOV. ▪ Post-amp outputs processed for all bands. ▪ Measurement made both AT and CT.	Collimator
Geometric Coverage Scanning: ±58.3° Pointing: 0°, +20°, −20° ±0.01°	Ambient Baseline	▪ SeaWiFS mounted on a rotary table. ▪ Scanner operating scan across collimator knife edge. ▪ Measure one channel at a series of scan positions.	
Dark Level Measurements	Ambient Baseline Vacuum	▪ Examine scan for response to built-in DC. ▪ Restore target.	
Spectral Coverage 402–422 bandpass 433–453 edge ±2 nm 480–500 range < 0.5 FWHM 510–530 555–575 655–675 745–785 845–885 stable ±1 nm	Ambient Baseline Filter Component	▪ Scan mechanism turned off. ▪ DC restoration from chopper in collimator. ▪ Monochromator spectral slit < 0.3 FWHM. ▪ Calibrated reference detector. ▪ Measure filter transmittance at six month intervals. ▪ Measure over temperature range.	Collimator with 0.25 m grating monochromator Spectrophotometer
Out-of-band Response < 5% integrated	Filter Component	▪ Transmittance measurement of filters.	Spectrophotometer
Within-band Spectral Differences		▪ Same as Spectral Coverage above.	
Band-to-band Registration (BBR) (0.3 IFOV)	Ambient Baseline	▪ BBR phased knife edge reticle in collimator. ▪ Measure both along-track and cross-track. ▪ All bands measured simultaneously. ▪ Scanner operating.	Collimator
Radiometric Sensitivity (NEδL)	Ambient Baseline Vacuum	▪ DC restore on bulkhead, scanner on. ▪ Integrating sphere source (minimum of 5 calibration levels), band SNR determined in this configuration. ▪ Source fills SeaWiFS solid angle. ▪ Test all bands.	48" Spherical Integrating Source (SIS)
Polarization Insensitivity ≤ 2% over ±45° 0.4 to 0.9 μ Measurements to Represent all Bands	Ambient Baseline	▪ Linear polarizer located in collimator. ▪ SeaWiFS on rotary table to test multiple zones of scan. ▪ Scanner operating, DC restore ▪ Glan Thompson polarizer in collimator. ▪ Test all bands.	Collimator SIS at Cal. Focus

Table 6 cont. SeaWiFS test plan summary.

Requirement	Development Phase for Test/Demo.	Demonstration Shift	Major Test Equipment Required
Dynamic Range	Ambient	▪ Part of radiometric sensitivity test.	SIS
Quantization	Subassembly	▪ Test electrical response.	
Modulation Transfer Function (MTF) MTF = 0.3 at Nyquist	Ambient Baseline	▪ Phased knife edge reticle for along-track and cross-track scanner used to scan PIKE reticles. ▪ DC restoration in normal manner. ▪ Measure all bands.	Collimator
Gains	Ambient Baseline	▪ Part of radiometric sensitivity test.	SIS
Transient Response Less than 1% overshoot Settle to 0.5% within 2 km	Ambient Baseline	▪ The instrument scans across the illuminated reticle at the focus of the calibrator. ▪ The transient response reticle will have five phase knife edges.	Collimator Transient Response Reticle
Radiometric Accuracy Absolute 5%		▪ Analysis. ▪ Test at angles.	
Radiometric Accuracy Relative 2%		▪ Analysis of on-orbit performance. ▪ Measure linearity.	
System Noise Measurements		▪ Use radiometric sensitivity test setup.	
Pointing Knowledge		▪ A combination of geometric coverage together with alignment and spacecraft data.	
Alignment References Knowledge of each pixel to: 60 arc sec. (3.4 mrad) < 60 arc sec. (3.4 mrad) Change throughout testing.	Ambient Baseline	▪ Measure boresight angle with respect to the alignment cube. ▪ Collimated target with SeaWiFS on the rotary table. ▪ Measure several scan positions and determine the interval from scan start to target. ▪ Mission stability by analysis. ▪ Scanner operating.	
Radiometric Stability and Repeatability Short-term stabiliy ±1% 2 wks Long-term stability ±2% 5 yrs Band-to-band repeatability 0.5%		▪ Subset of radiometric sensitivity. ▪ Long-term stability by analysis.	
In-flight Calibration Data Lunar Solar Diffuser	Analysis Component N/A	▪ Analyze detailed test. ▪ Measure diffuser spectral BRDF.	Goniometer

copies of all test data and anomaly reports and their disposition will be forwarded to GSFC. Moreover, it is anticipated that personnel from the GSFC SPO will be in close contact with their SBRC counterparts via telephone, electronic mail, fax, and site visits during all phases of system development. Formal action requests will be transmitted through the SeaWiFS Project Manager to Orbital Sciences Corporation (OSC) for subsequent transmittal to SBRC, if it is required.

It is anticipated that GSFC personnel will participate, as a minimum, in the SeaWiFS Preliminary Design Review (PDR), the Critial Design Review (CDR), radiometric calibration, initial baseline test, environmental tests and the post environmental baseline test. The level and extent of participation is to be determined (TBD). A summary of the major SeaWiFS milestones is given in Table 7.

Table 7. SeaWiFS major milestones.

Milestone	Month	Year
Preliminary Design Review	July	1991
Performance Assurance Plan	August	
Draft Calibration Plan	December	
Ground Software Plan	December	
Critical Design Review	December	
Design Completion	March	1992
Start Integration & Testing	September	
Final Calibration Plan	April	1993
Ground Software Completion	June	
Calibration	June	
Calibration Data to GSFC	July	
Complete Integration	July	
Satellite Launch	August	

2.2 Onboard Calibration

Onboard calibration and characterization activities will be governed mainly by 1) the acquisition and use of data acquired in flight from the solar measurements off the diffuser plate, 2) the solar measurements in scattering off the moon, and 3) the use of the spacecraft engineering data.

Two principles will guide the use of the diffuser in space. The first is to obtain the response of the SeaWiFS sensor to sunlight scattered off the diffuser over time frames that are short when compared to the time frames over which we expect changes to occur with the SeaWiFS sensor and the diffuser. The diffuser will be exposed at all times and will degrade. The second principle is to obtain enough measurements to discriminate between possible changes in solar irradiance and instrument drift. The present plan for solar calibration, given that SeaWiFS will be in a descending orbit, is to collect data over the South Pole (Fig. 15). The frequency of data collection has not been decided, but can be variable and as often as once per orbit. Most likely, there will be periods when frequent solar calibration is desirable, e.g., during the post launch verification period, and other times when the frequency can be relaxed.

The solar constant is known to vary over a solar cycle by an amount near 2 $\mathrm{W\ m^{-2}}$, and varies somewhat according to the expression,

$$S = 1371.33 + 0.0707 R_z \ \mathrm{W\ m^{-2}}, \qquad (1)$$

where S is the solar constant and R_z is the sunspot number. Of this variation, only about one third to one half can be identified to occur in the ultraviolet at wavelengths below 400 nm down to the Lyman alpha lines. The remaining variations must be at wavelengths longer than 400 nm, because the total radiated solar power below Lyman alpha wavelengths is an inconsequential fraction of the total solar constant and cannot contribute significantly to the remaining 1.3 $\mathrm{W\ m^{-2}}$ variation. Further, recently published measurements of the visible wavelength solar spectral irradiance, obtained by ground measurements from the Soviet Union, indicate the solar irradiance near 400 nm differs by greater than 8% from the published Neckel and Labs (1984) spectrum. (This data does not display any clear solar cycle variation over the three years for which the data was acquired.)

The variation with solar cycle of the solar constant is shown in Fig. 16 taken from Mecherikunnel and Kyle (1991), and is consistent with data sets from the Earth Radiation Budget Experiment (ERBE) and the Active Cavity Radiometer Irradiance Monitor (ACRIM) measurements program. Ground measurements of solar irradiance were shown to depart from the Neckel and Labs data (Burlov-Vasiljev et al. 1991), thus it is imprudent to devise a quantitative ocean color remote sensing program that is dependent on these Neckel and Labs data when SeaWiFS could be self-sufficient with a prudent calibration and flight observations scenario.

The prelaunch characterization of the diffuser must be based on the various usage scenarios that might develop from the application of the above principles. This will require the development of new approaches for using large aperture integration devices with large aperture instruments and solar diffuser plates. Laboratory and analysis approaches are being explored at the GSFC Standards and Calibration Office (Code 920.1) to develop such techniques.

The data analysis approach is the production of a solar flux data set. In the past, this approach has demonstrated the best quality control on the interpretation of the changes in the performance of the flight diffuser. (A similar approach to this will be employed on the SeaWiFS Project.) This approach is in use with the Backscatter Ultraviolet Spectrometer (BUV) instruments, which have continuously employed solar diffusers in space beginning in 1974. The schedule for the on-orbit use of the solar diffuser remains in the discussion stage. As with many other operational details, the SPO must reach an agreement with OSC on the details of plans for on-orbit activities. In addition, the long-term stability of the solar diffuser plate will dictate the plans for its use. If the diffuser degrades rapidly, frequent measurements of the moon will be necessary. Such a rapid degradation occurred on previous Landsat missions. However, the SeaWiFS design includes an attenuator plate that limits the exposure of the diffuser to solar flux by an order of magnitude. This new diffuser design should extend the operational lifetime of the diffuser to a period of several years.

The solar calibration will be made over the South Pole with the SeaStar platform oriented in the standard nadir direction. The sun can be viewed through the diffuser on each orbit of the satellite. These measurements will be made without tilting the SeaStar platform and will not require aiming the diffuser into the spacecraft's velocity vector, but will be made with the diffuser pointing opposite from SeaStar's line of flight. This scenario minimizes

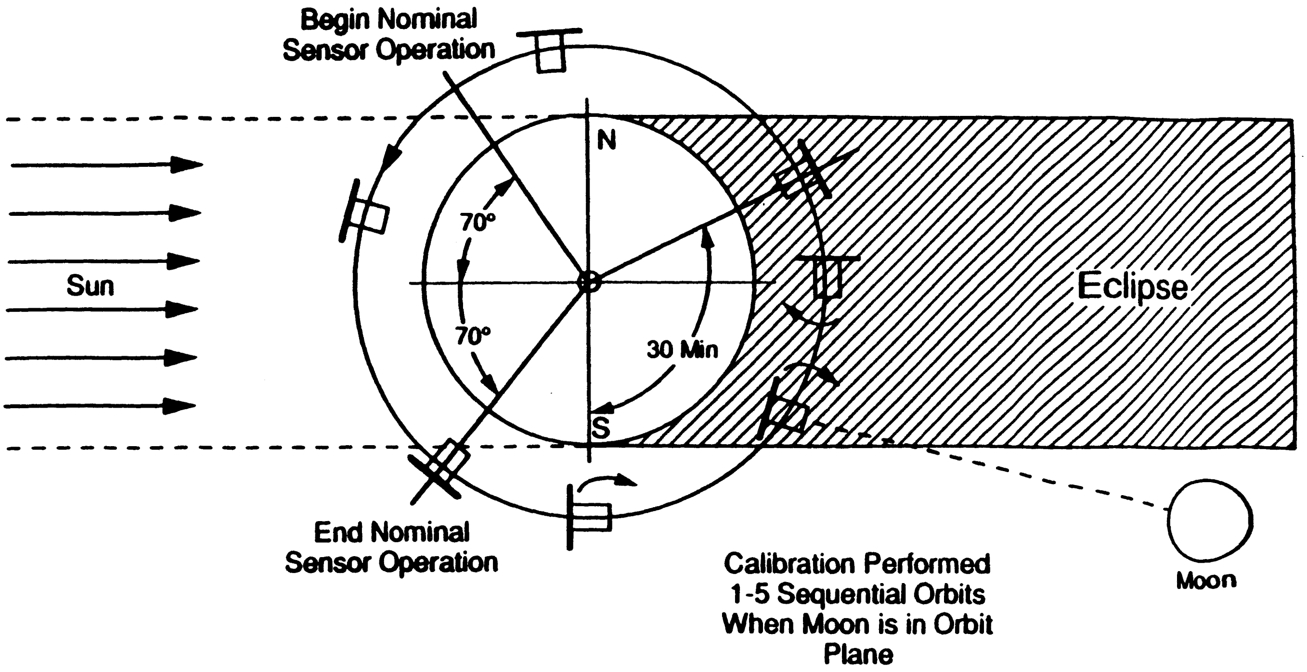


Fig. 15. SeaWiFS lunar calibration scenario (courtesy of Orbital Sciences Corporation).

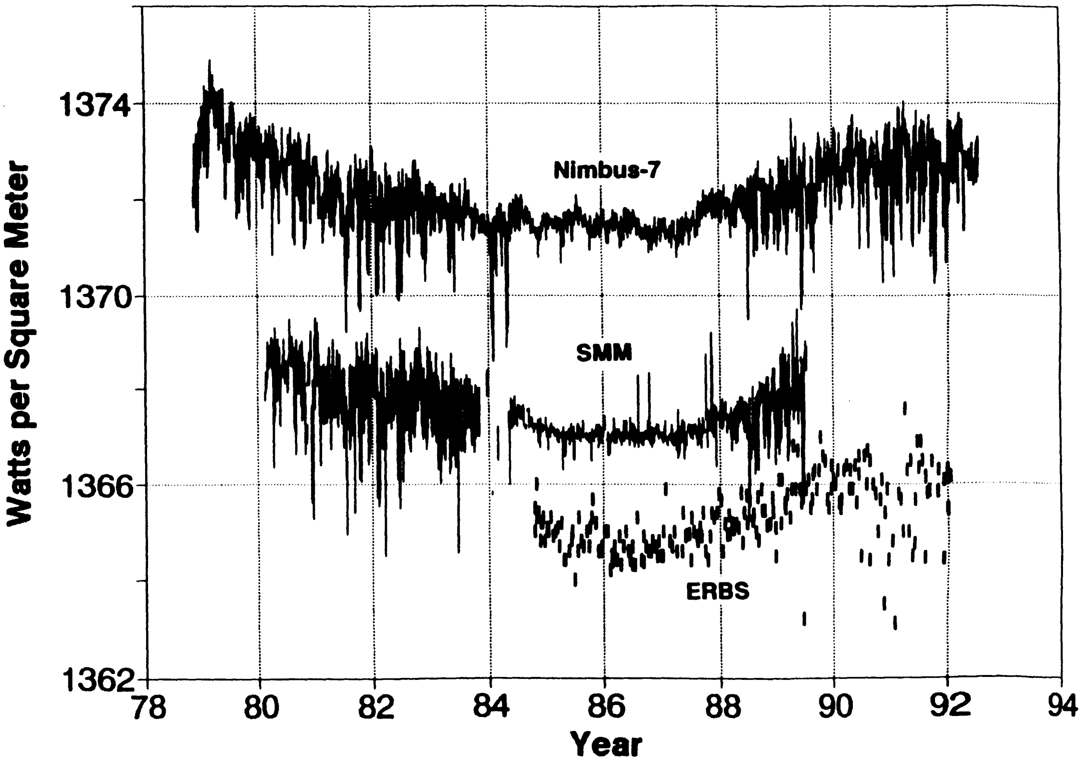


Fig. 16. Solar irradiance measurements from Nimbus-7, Solar Maximum Mission (SMM), and the Earth Radiation Budget Sensor (ERBS). Data from Mecherikunnel and Kyle (1991) and updated in 1992.

the loss of science data, in that science data will not be collected at solar zenith angles greater than 70° and much of the coverage would be over Antarctica anyway. However, some loss will occur, primarily during austral summer, when the instrument is tilted looking backwards and is commanded to a nadir tilt in preparation for a calibration.

The main principle to define the frequency of measurements of the moon is to track the degradation of the solar diffuser plate. In this concept, the instrument response to the sunlight scattered from the surface of the moon is compared to the instrument response to sunlight scattered off the surface of the flight diffuser. The surface of the moon is expected to be stable. The frequency of lunar observations is determined by the expected rate of change, with time in orbit, of the solar diffuser plate, but is modified by the noise in the lunar observations. The primary noise in the lunar observations is due to the relative inhomogeneity of the scattering from the moon due to changes in lunar phase angle and the portion of the lunar surface exposed to SeaWiFS. The moon will be available at a full illumination (full moon) approximately once a month. Analysis of the lunar observations will require establishing a lunar atlas and the tracking of equivalent albedo from locations across the moon as a function of illumination and observation geometry. A database of several months of data is expected to be needed at the beginning of the SeaWiFS mission to develop enough information to provide for corrections to the degradation of the flight diffuser. At that point, the instrument calibration can be corrected retrospectively. Later in the mission, the instrument calibrations can be verified in near real time based on the lunar observations, using the lunar measurements database. This scenario may have some adverse effect on the quality of the SeaWiFS calibration provided early in the mission for data to be used for commercial purposes. A lunar viewing scenario is provided in Appendix C.

There must be an initial characterization of both the lunar view and solar diffuser measurements at the start of the mission. Several measurements on adjacent orbits will be necessary to determine the 95% confidence limits for the solar measurements. Such measurements will be necessary on a daily basis until the degradation rate of the diffuser is determined. After this, a long-term operational schedule for solar diffuser measurements can be established. A baseline must also be set up for lunar measurements. The long-term frequency of lunar measurements (perhaps 2–4 times a year) will be set by the long-term stability of the solar diffuser. Initial steps to prepare for the lunar calibration have been initiated. SPO has funded Kenneth Voss and Howard Gordon, at the University of Miami, to collect and analyze an initial set of radiometric observations of the moon. Voss collected the first set of data from Mauna Loa in May 1991. Additional observations will be collected at Miami. Also, EOS is supporting a lunar reflectance mapping study scheduled to begin in 1994.

Another aspect of the calibration program will be the routine review and archiving of certain spacecraft and sensor engineering telemetry. It should be emphasized that these data were not routinely scrutinized and archived by the Nimbus-7 CZCS NET. This made the task of correlating the CZCS degradation with spacecraft environmental parameters and operation procedures impossible. The telemetry parameters that will be monitored are given in Table 8. First order data processing will include simple time series and correlation analyses, but a detailed procedure has not been designed at this time.

Table 8. SeaWiFS telemetry parameters to be monitored.

Analog Supply Voltages	Number of Sources
Power Supply Voltages	8
Motor Drive Currents	4
Scan Speed Error Signal	1
Scan Synch Error Signal	1
Focal Plane B1,2 Temperature	1
Focal Plane B3,4 Temperature	1
Focal Plane B5,6 Temperature	1
Focal Plane B7,8 Temperature	1
Total	18

2.3 Post-launch Calibration

The post-launch vicarious calibration of SeaWiFS requires accurate measurements of the water-leaving radiances which are then compared with the estimated values derived from the satellite using a specific atmospheric correction model. Thus, the approach treats the calibration as a combined sensor atmospheric correction system. In order to verify a vicarious calibration, it is best to select a data collection site that has minimal variability in its optical properties, i.e., open ocean Case 1 water with low pigment concentrations. Also, a large number of *in situ* and satellite observation pairs are needed to provide statistical confidence in the comparisons. For most latitudes, coverage will be every other day and cloud cover will interfere a significant percentage of the time, so the best approach is a fixed optical mooring that can be serviced periodically. The optical mooring provides the capability of collecting data at a higher frequency than the satellite coverage. Of course, additional data will be available from ship data, but not at a regular frequency.

The sensor degradation of the CZCS was large with significant high frequency variability (as shown in Fig. 6), thus, it is essential that continuous accurate field observations be available. In order to specify what observations are required for the vicarious calibration and both atmospheric correction and bio-optical algorithm development, a workshop was held in Monterey, California in April 1991. The proceedings of the workshop, *Ocean Optics Protocols for SeaWiFS Validation* (Mueller and Austin 1992), has been published as Volume 5 of the SeaWiFS Technical Report Series. The list of required variables for the vicarious calibration are shown in Table 9.

The philosophy of the SPO is to support field programs whose data can also be applied to other planned missions such as OCTS and MODIS, and to begin the development of a comprehensive archive of high quality data that are suitable for satellite calibration and bio-optical algorithm development. Under EOS sponsorship, Dennis Clark of NOAA, has begun the design, fabrication, and field testing of mooring and ship deployed radiometers for this purpose. For the vicarious calibration, the radiometer is coupled to an optical mooring. Components of the optical mooring include the collectors, fiber optic links to the radiometer, the power subsystem, and a telemetry subsystem. Schematics of the optical buoy system and mooring configuration are shown in Figs. 17 and 18, respectively.

The SPO will augment EOS support in order to expedite these development efforts so that these systems can be in place before launch. These systems are designed to transmit data daily to land based sites via satellite communication links. Thus, comparison of satellite and *in situ* data can be achieved on a daily basis. The SPO will routinely schedule local area coverage (LAC) data collection over the mooring site. The mooring site will be adjacent to the Joint Global Ocean Flux Study (JGOFS) Hawaii time series mooring. This simplifies logistical support and ensures the routine collection of a variety of other useful water quality parameters. The mooring and JGOFS data sets will be kept on-line in a database at GSFC as part of the calibration program. The first deployment of the optical mooring, without the radiometer, was in August 1991, in Monterey Bay. The mooring fabrication is being done at Moss Landing Marine Laboratory. The test deployment of the mooring with the radiometer is scheduled for early 1992.

Under the terms of the contract between NASA and OSC, NASA must determine if the SeaWiFS data meets the specifications outlined in the contract. This decision must be made within 120 days of launch. In order to certify the sensor performance and calibration, the SPO will support at least one verification cruise. This cruise will also provide for the initialization of the operational atmospheric correction algorithm and the validation of the bio-optical derived products. For this purpose, a clear water region with relatively low cloud cover is required. The present site selection is off Baja, Mexico, which is readily accessible from San Diego. The cruise plan calls for a full complement of *in situ* marine and atmospheric optical and water quality observations, as outlined in the Monterey Workshop proceedings. A vessel for the Baja validation cruise has not been identified at this time.

Arrangements for other cruises during the 120 day period are being pursued by the SPO and by other agencies and international groups. The strategy is to hold a workshop near the end of the 120 day period where those who participated in validation cruises could present their preliminary findings. Based on these reports and the analyses of the satellite data performed by the SPO, a recommendation will be drafted. To meet this deadline, all parties, including the SPO, must be prepared to turn data around in near real time. This requires all issues regarding satellite data processing software (imagery, ephemeris, and engineering), ancillary data format and data exchange scenarios, data quality control, and data distribution be resolved before launch. It also requires *in situ* data be processed during the field programs.

As mentioned earlier, a joint effort with EOS MODIS calibration development activities using the NASA Earth Resources-2 (ER-2) aircraft is being considered as a fourth calibration methodology. The technique is currently being used for the calibration of the Advanced Very High Resolution Radiometer (AVHRR) on NOAA satellites. Congruent observations of radiance from the satellite sensor and the ER-2 (Fig. 19) allow transfer of the radiance calibration of a radiometer on the ER-2 to the satellite sensor (Hovis et al. 1985, Abel et al. 1988, and Abel et al. 1991). Spectral radiance measured from the ER-2, accurately corrected to satellite altitude, is integrated across the spectral response profile of the satellite sensor and compared with the sensor measurement to derive sensor gain. The only major assumption of the method (an assumption shared by the buoy calibration) is that the spectral response profile of the sensor bands does not deviate from pre-launch measurements. The absolute accuracy of the resulting gain of the satellite sensor is estimated to be ±3%, including calibration of the ER-2 radiometer (Guenther et al. 1991). Precision is estimated at ±2%. Both uncertainties may be reduced significantly through improvements that are now in the planning stage. It is desirable to execute three underflights per year to adequately establish the long-term satellite sensor performance. The cost incurred by the SPO would be flight expenses only, which can be minimized by conducting the missions out of NASA/Ames Research Center.

SeaWiFS performance will be monitored using solar, lunar, and vicarious calibration techniques. Lunar calibration will be possible once per month (Appendix C). Solar calibration using the diffuser plate will be at least as frequent. Because of the satellite's swath, comparison with the optical mooring data will, at best, be provided every other day. Ultimately, the buoy's vicarious calibration results will be used because they are tied to the primary derived products, the normalized water-leaving radiances. In the vicarious calibration, errors are attributed solely to changes in the calibration. Differences between the onboard calibrations and the vicarious calibration will provide a better indication of the source and magnitude of errors in the vicarious calibration, e.g., in the atmospheric correction algorithm.

In the CZCS vicarious calibration, the mean $L_{WN}(520)$ and $L_{WN}(550)$ for the clear water regions of the global

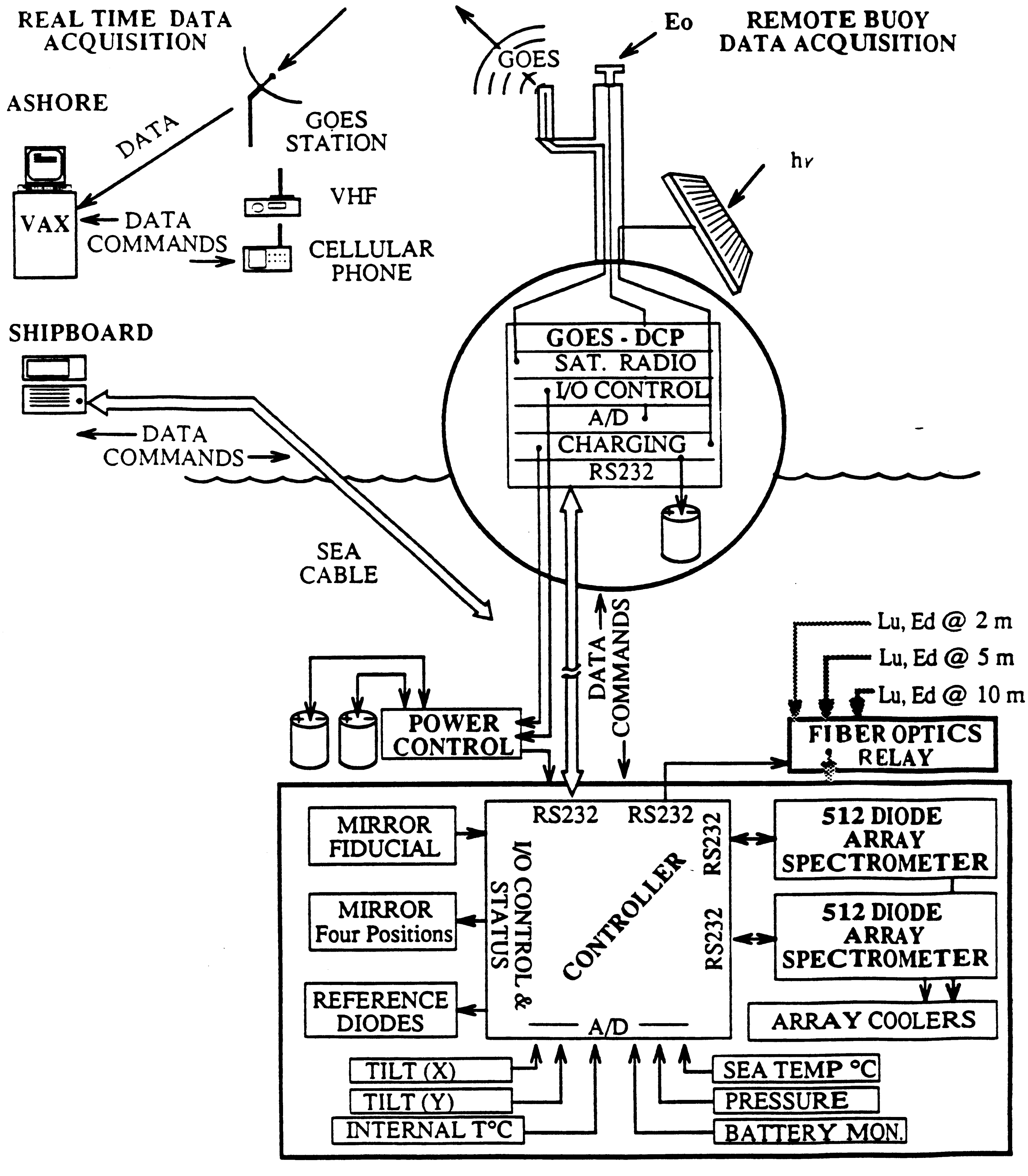


Fig. 17. Schematic of the SeaWiFS optical buoy system (courtesy of D. Clark).

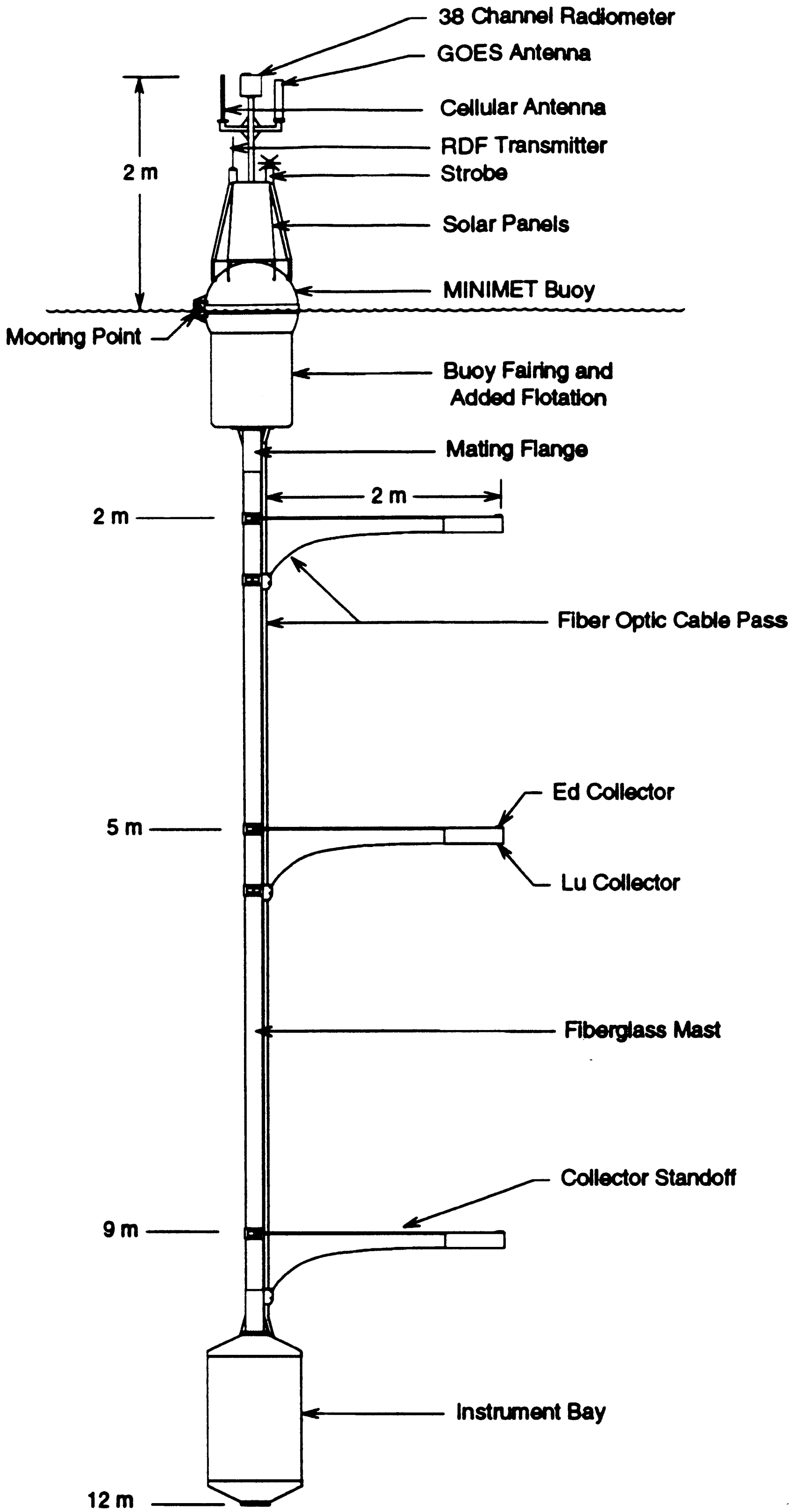


Fig. 18. Drawing of the SeaWiFS optical mooring (courtesy of D. Clark).

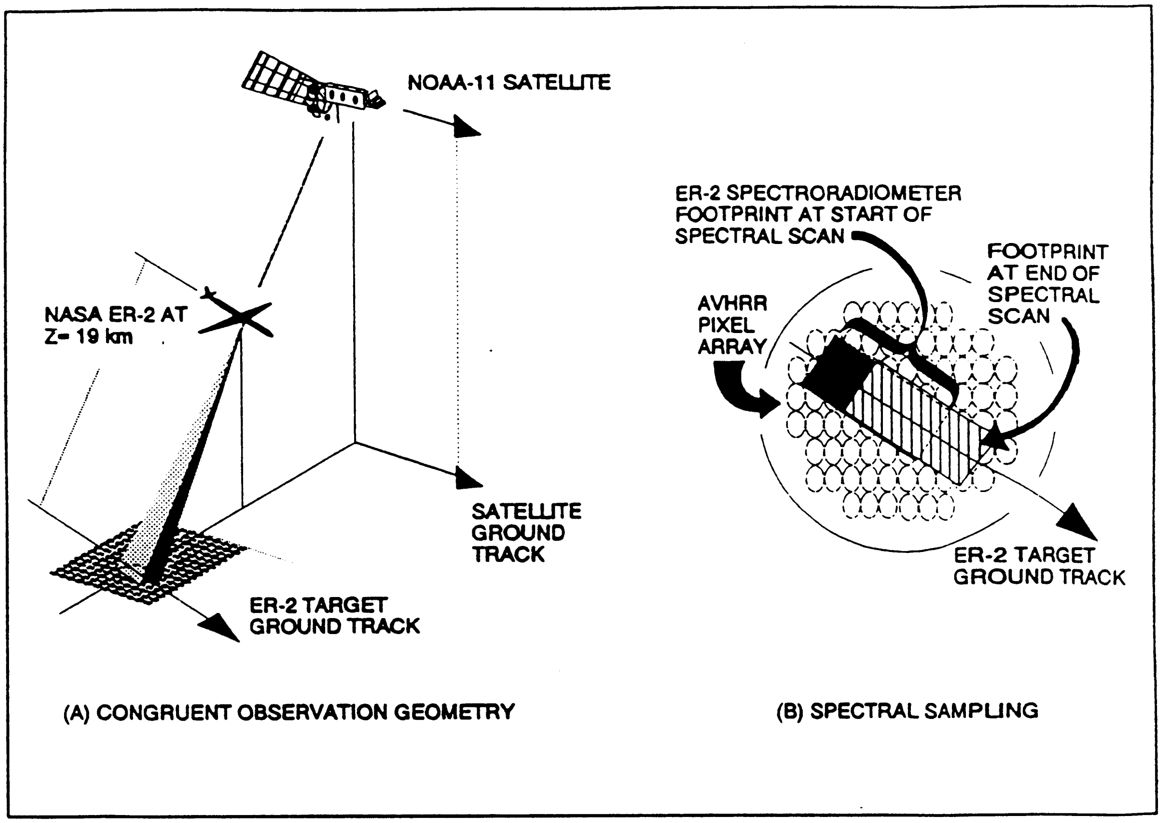


Fig. 19. Aircraft calibration technique: **a)** the aircraft radiometer observes the target along the same view vector as the satellite sensor. The two instruments have different footprints, and the ground tracks of the aircraft may be different from the satellite track, and **b)** the radiance for each wavelength in a scan corresponds to a different footprint. Corrections are applied in the data analysis to optimize spatial registration between the satellite and aircraft data.

ocean were assumed to be constant for pigment concentrations estimated to be less than 0.25 mg m^{-3}. The basis of this approach is the data set collected by the NET (Fig. 1), which does not account for regional and seasonal variations in the normalized clear water radiance values. While this restriction may not have been serious for the CZCS, it does undermine the objectives of the SeaWiFS mission, which has very stringent accuracy requirements (Section 1.3).

Additional procedures will be executed to check the consistency of the intergain calibrations. One method will be to sweep through the gains on consecutive scans over a clear water region to determine if each gain yields statistically similar total radiances. The instrument can be commanded to change gains on a scan line-by-scan line frequency.

3. ALGORITHM DEVELOPMENT

3.1 Derived Products

The SPO plans to produce three groups of level-2 derived products: *CZCS-type*, SeaWiFS *baseline*, and *potential* SeaWiFS products. A differentiation is made between CZCS-type pigment and SeaWiFS baseline “chlorophyll-like” pigment concentrations. The CZCS-type pigment is the summation of chlorophyll a and phaeophytin concentrations. The 412 nm band was included for the purpose of separating viable pigment from degradation by-products. A more complete description of these products is given below.

CZCS-type Products:

- Three-channel (Clark and Gordon) $L_{WN}(443)$, $L_{WN}(520)$, and $L_{WN}(565)$ pigment algorithm.
- Atmospheric correction with $e = 1.0$.
- “Certified” and ready at launch.
- Produced routinely: five L_{WN}, $K(490)$, pigment, three L_a, and a confidence or error field.

SeaWiFS Baseline Products:

- Developed by the SPSWG with prelaunch cruise and other data.

- On-line at launch for evaluation and further development.
- "Certified" after post-launch validation cruise.
- Includes: wind-dependent glint correction mask, aerosol and Rayleigh interaction, variable epsilon aerosol correction, initial Case 1 and 2 identification and corrections, and CZCS-type products plus chlorophyll *a* concentration, non-chlorophyll absorbance correction value, and excess scattering correction value.

Potential Baseline Products:

- Some other possible products that may be developed by the SWG or other principal investigators with pre- and post-launch data.
- Routine project production following SWG certification and headquarters approval: accessory pigment concentrations, primary productivity, degradation product concentrations, coccolith or $CaCO_3$ concentration, sediment concentration, aerosol concentration and type, I_0, and other to-be-specified products.

The SPSWG has specifically expressed a requirement for continuity between CZCS and SeaWiFS products. This approach, if strictly adhered to, has several ramifications. It would preclude incorporation of improvements in the bio-optical algorithm, e.g., use of a 3-band pigment algorithm (Muller-Karger et al. 1990) and use of bio-optical algorithms based on normalized water-leaving radiances. It would require the same atmospheric correction algorithm be used as the one applied in the global CZCS processing. It would require that only the NET data used in producing the CZCS bio-optical algorithms be used and these data would need to be analyzed for the SeaWiFS bands. It is probably better to reprocess the CZCS data before the SeaWiFS launch than to produce SeaWiFS products strictly similar to the existing global processing products. Reprocessing would be advantageous because it would allow (1) the use of a 3-band normalized radiance pigment algorithm, 2) the use of an improved atmospheric correction algorithm, 3) the development of an improved calibration (Hay et al. 1991) and 4) the development of a prototype operational SeaWiFS processing and calibration and validation system. The CZCS-type products listed above imply the use of advanced algorithms.

The level-3 products will be space-time average fields binned into standard grid, presumably at 9 km resolution so as to be comparable to the AVHRR sea surface temperature (SST) fields being produced by the AVHRR Pathfinder project. Issues that must be addressed for the level-3 products are: what statistics should be computed, and what error analyses should be incorporated as products.

Inevitably, changes in the operational derived product algorithms and requirements for new derived products will be suggested as more is learned about bio-optics and atmospheric corrections during the course of the mission. Such additions and modifications are essential to providing the highest quality products possible and for producing products that the research community routinely need. A procedure for authorization of algorithm changes and new products must be defined.

Recommended additions and alterations must first be brought to the attention of the SeaWiFS Project Scientist through a formal, written proposal. The proposal must contain a detailed textual description of the algorithm, the data and theory used to develop it, the limits of its applicability, the methodology for validation, and its potential importance to scientific problems. The people involved in reviewing the proposal are the NASA Headquarters Ocean Color Program Scientist, the SeaWiFS Project Manager, the SeaWiFS Project Scientist, the SeaWiFS Calibration and Validation Manager, the SeaWiFS Data System Manager, and the SeaWiFS SWG. They will determine the importance of the algorithm or product and feasibility of its implementation based on the following criteria:

1) *Publication in the open literature:* While submitted or well tested algorithms must also obtain approval, publication in a peer reviewed journal substantially increases the likelihood of approval.
2) *Significance:* The ability of the algorithm to improve current observations or to extend the usefulness of SeaWiFS data into new areas of scientific importance is a major factor in its selection. The potential demand by the science community is critical.
3) *Generality:* Greater weighting is given to algorithms that apply universally, i.e., those not restricted to specific regions or seasons.
4) *Accuracy:* The ability of the algorithm to perform within the stated limits of its accuracy based on independent validation data.
5) *Resources:* If the algorithm requires substantial upgrading of the data system (hardware and/or software), then the impact on the processing system in terms of manpower, cost, and system resources (central processing unit (cpu), storage, etc.) must be evaluated. If it is determined that the modification or addition is justified, then an implementation plan will be developed.

3.2 Database Development

The amount of historical data suitable for SeaWiFS bio-optical algorithm development is very limited because of the specific suite of simultaneous observations and the radiometric accuracies required. Even for the CZCS, few algorithms have been published and these hardly ever show agreement. For example, Fig. 20 shows three different Case 1 algorithms (Morel 1980, Mitchell and Holm-Hansen 1991, and Gordon per. comm.) and indicates a sizable range of

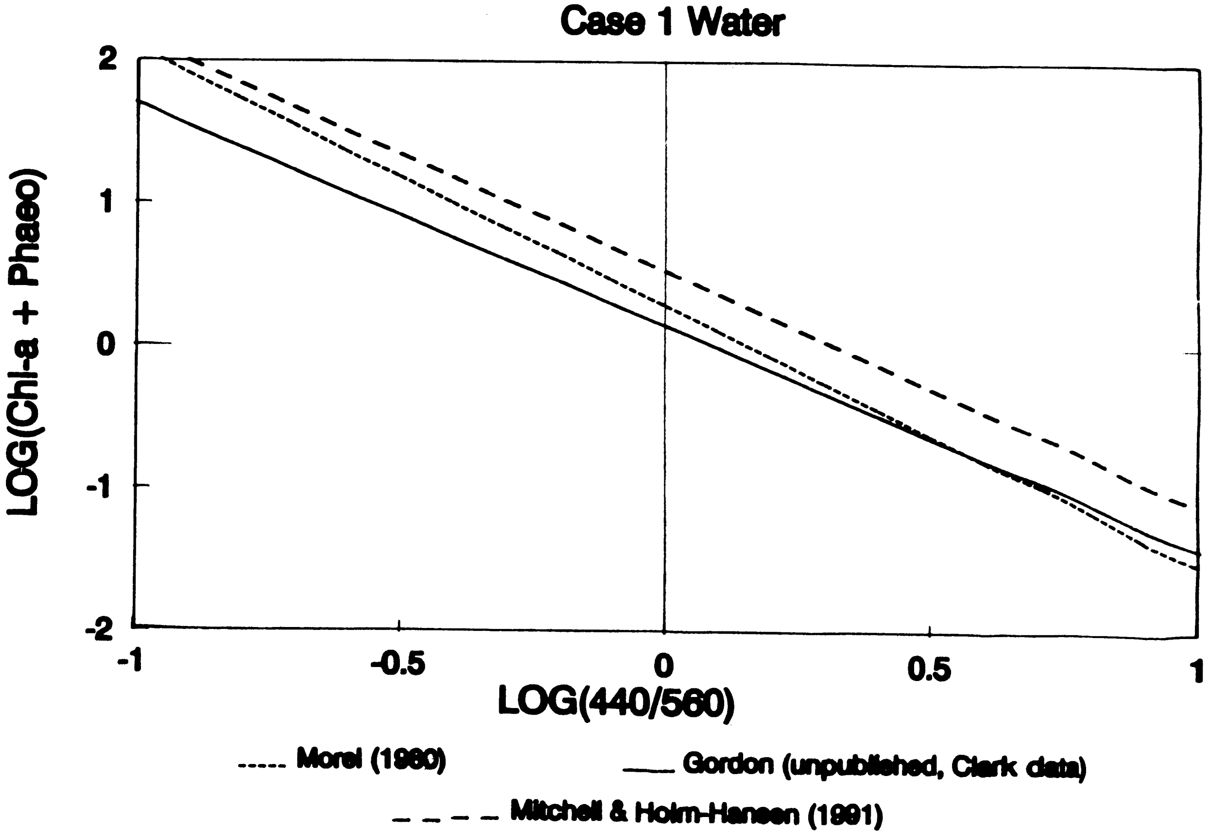


Fig. 20. CZCS bio-optical pigment algorithm comparison.

values for a given radiance ratio (note that the axes are log-log). The differences are the result of data collected from regimes having different bio-optical properties and probably from differences in instrumentation and sampling techniques. In order to minimize observational error, the SeaWiFS Monterey Workshop participants outlined the observations and sampling protocols required for bio-optical algorithm development (Table 9). Note that this suite of observations includes in-water and atmospheric optical, and water quality measurements which will require 12–15 people on a cruise.

In order to begin the development of a high quality bio-optical algorithm database, the SPO is funding Mr. Dennis Clark to re-analyze the CZCS NET including the computation of normalized water-leaving radiances. Normalization of water-leaving radiances removes the influence of solar zenith angle and should improve the correlations with water constituents. The SPO will solicit other data sets of comparable quality from individual investigators. This database will be used to formulate and compare advanced CZCS-type algorithms with the standard algorithms and to develop preliminary SeaWiFS chlorophyll-like pigment algorithms. The acquisition of the historical data sets will require the implementation of quality control, documentation, and cataloging procedures and the design of a database structure suitable for bio-optical data with a user friendly interface. This development will also handle bio-optical data sets for SeaWiFS sponsored field programs that will begin in 1992.

In situ near-infrared observations are needed for advanced atmospheric correction algorithm development in turbid waters in order to avoid the assumption that water-leaving radiances at 665, 765, and 865 nm are zero. For the CZCS data, attempts were made to work around the questionable assumption that water-leaving radiance at 670 nm is zero (Smith and Wilson 1981). The Smith-Wilson iterative algorithm was based on data from the Southern California Bight and is not applicable to most coastal regimes, which have differing spectral characteristics.

Historical data, unfortunately, in the near-infrared is questionable because of instrument self-shading as indicated by recent theoretical studies by Howard Gordon (per. comm.). An effort to correct the CZCS NET data is being considered by Clark and Gordon, but no results have been derived to date. To make reliable observations, the instrument must be removed from the light collection point, and the collection be made very close to the surface. Because of the very shallow optical depths in the near-infrared, the surface must be placid. Clark is developing a collector coupled to a radiometer via a fiber optic link. This sensor system was field tested in mid-1991. Probable turbid water data collection sites in 1992 include Chesapeake Bay, Moss

Landing lagoon in Monterey Bay, and Lake Pend Oreille, Idaho in collaboration with the Office of Naval Research (ONR) sponsored Closure Experiment.

3.3 Research Cruises Program

Because of the number of observations and personnel required for bio-optical algorithm development (Table 9), dedicated cruises are necessary. Cruises of opportunity are not usually amenable to the algorithm data collection requirements because of the limited number of berths available and conflicts over cruise planning, such as station locations, and ship resources, e.g., winches, wire time, and laboratory and deck space. The SPO's approach is to support a minimum of one dedicated cruise per year and to provide supplementary funding to field programs whose objectives can easily accommodate the requirements of bio-optical algorithm development. One primary consideration is ship time, as NASA Headquarters will provide funding for a dedicated cruise in FY94 only.

In order to optimize the amount of data that is collected in FY92–FY94, the SeaWiFS Project must support at least two teams of investigators. The first team includes members of the MODIS instrument team: Dennis Clark, Kenneth Carder, Howard Gordon, and Wayne Esaias. The MODIS project will provide most of the support for this group. Dr. Stanford Hooker of the SPO will work with Dennis Clark in the development of a shipboard data collection system. The SPO views the collection, storage, and preprocessing of the complete suite of *in situ* observations as a major element of the bio-optical data set development activity.

The architecture for the SeaWiFS field computing system is based on the unique requirements of collecting data at sea. First, the media used to store, retrieve, and display data should be removable so data can be archived daily; thus, in the event of media corruption or damage, one day's worth of data is put at risk. Second, the peripherals, including the computers where possible, should support a common architecture, so they can be freely reassigned in the event of unexpected losses. Third, for distributed systems, that is, systems where data is collected on one computer and processed on another, the architecture should provide an electronic network for fast and reliable data transfer. For optical data collection there is the additional requirement that many of the computing resources need to be small and mobile so the instruments and the computers that control them can be located where the measurements are taken.

The SeaWiFS field computing network is divided into separate acquisition and processing units based on the measurement or processing task each performs:

1) Satellite Imagery and Error Analysis (comprised of a real-time error analysis workstation and an image retrieval and display computer),
2) Hydrographic Data Reduction and Analysis (HYDRA) system, which is comprised of a CTD, Global Positioning System (GPS), and profiling transmissometer),
3) Submerged *In Situ* Spectral Radiometer (SISSR),
4) Radiance Distribution (comprised of sky and in-water, as well as optical thickness radiometers),
5) *In Situ* Station Measurements (comprised of particle and pigment analysis),
6) *In Situ* Along-track Measurements (composed of fluorometer and transmissometer systems),
7) *In Situ* Data Quality and Control, and
8) Primary Productivity.

A schematic of the field computing system is shown in Fig. 21. As can be seen in the figure, the system naturally divides in two: the larger multifunctional processors and the smaller single instrument data collectors. The apparent proliferation of the latter is a consequence of the single point-of-control needed for the instrumentation. That is, each instrument requires an individual operator in near continuous interaction with the controlling computer. Since all of the instruments will be making measurements a few hours before and after noon, they cannot share a duty cycle with a single computer. Despite the designed separation of function and purpose, there is extensive media commonality and a certain amount of hardware and software redundancy in the system to allow for unexpected computer or peripheral losses, which is not explicitly shown in the figure.

The computers communicate and exchange data along an Ethernet thinwire spine. The backbone of the spine is comprised of the larger computers requiring a central location and greater system stability because of their need for regular system management. The smaller data collection microcomputers, which are moved around with their attendant instruments, are connected to the spine through a fan-out unit because they are most likely to be in difficult places to access and run Ethernet cable to. In addition to easing cabling concerns, the fan-out unit ensures a greater degree of backbone stability or integrity by "insulating" the backbone from computers that are likely to go on- and off-line with some regularity. In the event of a complete network failure, the Macintosh computers can communicate using Apple's built in AppleTalk network, RS-232 serial lines, or media swapping (the so called "hand net") . For the other computers, only the latter two options are alternatives.

The second group will be primarily composed of investigators supported by the Navy for SeaWiFS related field studies. The Navy has indicated that it would support dedicated cruises with Navy investigators for SeaWiFS algorithm development. James Mueller at the Center for Hydro-Optics and Remote Sensing (CHORS) at San Diego State University will be the primary SPO supported inves-

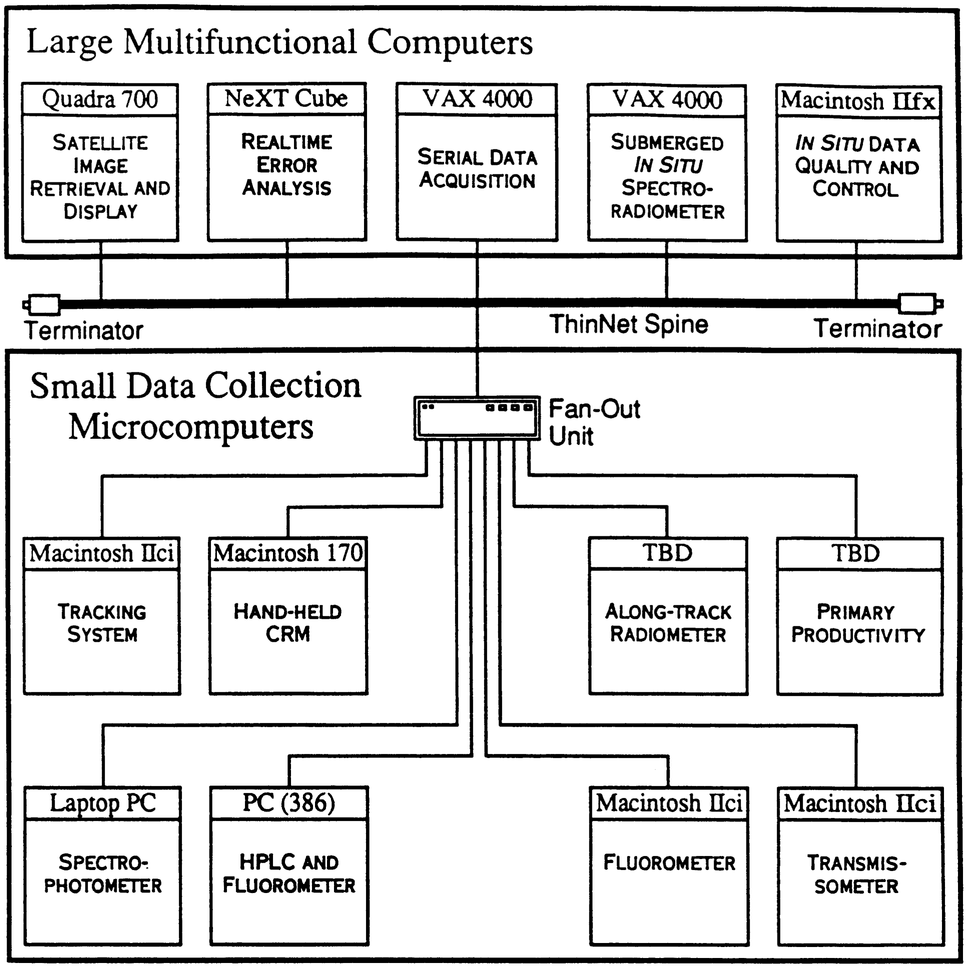


Fig. 21. Shipboard computing network.

tigator in this group. He has been selected because of the high level of technical expertise at CHORS and their existing calibration facilities which can support calibration of other NASA supported investigators instrumentation. Support to CHORS will augment the Navy's sampling program to meet SeaWiFS requirements for algorithm development. The strategy assumed by the SPO is to fund investigators who have the required experience and instrumentation for the in-water optics and then have both teams subcontract to other investigators for specific observations, e.g., High Performance Liquid Chromatography (HPLC) pigment concentrations, which they are not equipped to make. Fig. 22 shows field experiment opportunities in the 1991–94 period which have been identified to date. The present plan with the Navy is to conduct a cruise in October 1992 (R/V *U.S.N.S. DeSteiguer*), with a probable cruise during the post-launch verification period.

There will be some coordination with JGOFS activities. David Siegel (of the University of California at Santa Barbara) has been funded by the NSF to conduct routine bio-optical observations at the Bermuda Time Series Station. The SPO will provide some support for radiometer calibration at Bermuda. Also, the JGOFS Steering Committee has agreed to consider dedicated bio-optical cruises within the Indian Ocean and Southern Ocean programs. Presumably, the SPO would support a team of investigators to participate in those survey legs and NSF would provide the ship time. Augmentations to approved field experiments of opportunity, to include additional data collection for algorithm development, will be handled on a case-by-case basis. In such cases, the field program would be supported at whatever level the SeaWiFS budget allows, depending on how adequately the program meets the SeaWiFS observational requirements, the location of the survey, and the level of support requested.

The selection of sites for field studies will be determined on the adequacy of the existing atmospheric correction and bio-optical algorithms. First priorities will be to obtain initial Case 1 data sets for chlorophyll-like pigments and Case 2 data for the atmospheric correction because there is little or no data presently available for the SeaWiFS baseline product algorithms. These can be obtained from field programs proximate to the U.S. However, as indicated in Fig. 4, regional algorithms will be needed. For example, high latitude data will be required from the polar oceans where phytoplankton are photoadapted to low light levels and, therefore, have quite different absorption characteristics. These environments can also support very high concentrations, e.g., the Bering Sea where surface pigment concentrations can be greater than 40 mg m^{-3}. Also, regions where atmospheric dust modifies the optical properties of the atmosphere and the ocean, e.g., the tropical Atlantic Ocean and the Arabian Sea, have proven to be troublesome. Much of the CZCS data off N.W. Africa was discarded during the global processing quality control because of anomalous water radiances and aerosol patterns evident in the water-leaving radiance and pigment fields.

Another topic of concern is the anomalous water-leaving radiances produced in coccolithophores blooms. These blooms are observed in most regions of the ocean and can be quite expansive during the North Atlantic spring bloom. In order to develop accurate estimates of the global derived product fields, algorithms designed to handle these and other problems are needed and can only be derived from an extensive database of high quality observations. An adequate database does not exist at this time.

One of the contractual requirements imposed by the SPO on supported investigators is the rapid delivery of data to the SPO. The data will need to be calibrated, quality controlled, and well documented. Some pre-processing will also be needed for the calculation of some parameters such as the normalized water-leaving radiances. The Monterey Workshop proceedings outlines some recommended procedures. Because of the rapid turnaround requirement, especially for the post-launch verification, the observations will need to be processed in near real time. Thus, it will be necessary for the investigators to have the necessary computing capabilities on the ship with appropriate software and mass storage. It will also require that data management, data format, and documentation specifications be well developed. It would be preferable that some set of standards for each data type be agreed upon by the teams. The minimum requirement is that the SPO have verified ingest routines in place prior to each cruise to handle each investigator's data. These data will be accumulated and consolidated by the SPO at GSFC. Specifics on documentation, ancillary data, e.g., instrument calibration and characterization data, and format issues have not been addressed to date and will need to be discussed at a cruise planning workshop. Presently, two cruise planning meetings per year are being scheduled.

3.4 Algorithm Development

The data obtained from the field program will be ingested into SPO on-line databases at GSFC. These data will be accessible by SPO approved investigators for the development of advanced bio-optical and atmospheric correction algorithms. These investigators will include not only members of the field program teams, but also others who contribute data of comparable quality and investigators selected by the SPO to work on bio-optical algorithms. The protocols regarding data rights, data access and distribution policy are outlined in Appendix B.

Having the historical and bio-optical cruise data in a well documented form in a common database system designed for such data will allow much more flexibility for investigators to review data and to try more innovative approaches than has been possible in the past. The SPO desires to promote new methodologies. One activity the SPO will support in-house is the capability to independently review, implement, and compare algorithms proposed by the research community. This will require a detailed knowledge of the data sets, data pre-processing procedures, and relevant radiative transfer theory. The data processing required for these analyses will be performed separately from the routine SeaWiFS data processing. Algorithm verification studies will require the collection of data not included in the development of empirical algorithms. For example, field observations of pigment concentrations from process studies that do not include in-water optics will be available from many sources and can be used to test algorithm performance. Given the location and times of field observations, satellite products can be derived from the on-line level-2 normalized radiance fields. These data sets (field data, satellite radiances, algorithm products) can be stored in on-line databases for quick access. This match-up data analysis will be updated as field data is received and includes radiance data from the calibration mooring and post-launch bio-optical and sensor calibration cruises.

Having the SPO independently review the performance of the operational and proposed algorithms is essential. Proposed changes or additions to the suite of operational products will require approval of the SPO and the SWG (after the NRA). The best approach would be to require a formal written proposal from the investigator which outlines the algorithm, its limitations, the data used in deriving it, etc. This proposal would be reviewed by the SPO and the SWG. The SPO would conduct its own evaluation of the algorithm's performance and computational requirements. Then, based on the results of these reviews, the algorithm would be adopted or rejected.

3.5 Atmospheric Correction

Figure 4 shows the atmospheric correction algorithm that was employed for the CZCS. The algorithm assumed the following (Gordon et al. 1983a, Gordon and Castaño 1987, and Gordon et al. 1988):

1) For a given scene, the aerosol type, as characterized by the Ångström exponents, are constant. In the global CZCS processing, the Ångström

Activity Name	Contact(s)	Objectives	1991			1992											
			O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Monterey Bay, CA	Dennis Clark Chuck Trees Stan Hooker Bill Broenkow	Test Dennis's optical instrument. Case 1 pigments.	◆														
Bermuda (JGOFS Site)	Dave Siegel	Pigments and optical measurements.				◆	—	—	—	—	—	—	—	—	—	—	—
Lake Pend Oreille, ID ONR Closure Experiment	Ron Zaneveld Ken Voss Jim Mueller Chuck Trees Stan Hooker Alan Wiedeman SRI, TetraTech	Case 1 pigments, particulates, path radiance, radiance distribution, point spread function, reflectance, instrument shadow.								◆							
Monterey Bay, CA R/V Destieguer and R/V Pt. Sur	Dennis Clark Chuck Trees Stan Hooker Bill Broenkow Ken Voss	Case 1 pigments, atmospheric correction and buoy test. (Promoted to major engineering shake-down cruise.)											◇	◇			
Baja, Mexico Mexican R/V Puma	Dennis Clark Chuck Trees Stan Hooker S. Alvarez-Borrego Reuben Lara-Lara	Test D. Clark's optical instruments and buoy. Case 1 pigments. (Major engineering shakedown cruise.)														◇	◇

Activity Name	Contact(s)	Objectives	1993											
			J	F	M	A	M	J	J	A	S	O	N	D
Bermuda (JGOFS Site)	Dave Siegel	Pigments and optical measurements.	—	—	—	—	—	—	—	—	—	—	—	◆
CalCOFI (Quarterly Cruises)	Gregg Mitchell	Bio-optical algorithm validation.	◇			◇			◇			◇		
Gulf of Mexico	Ken Carder Jim Mueller Alan Wiedeman Bob Arnone	Instrument shake-down, Case 2 pigments, algorithm development.			◇	—	◇							
Arabian Sea	Sharon Smith Barney Balch	JGOFS mini-process study.						◇	—	◇				
Lanai, Hawaii (Possible move to JGOFS site after 2 quarters)	Dennis Clark Bill Broenkow Stan Hooker	Mooring and optical buoy deployment (can be increased in scope).								◇			◇	
Mediterranean Sea	Ken Carder Jim Mueller Alan Wiedeman Bob Arnone	SeaWiFS validation, Case 1 and 2 pigments, radiometric calibration.									◇	—	◇	
Western Pacific R/V Atalante	J. Picaut Cecile Dupouy Andre Morel												◇	
Baja, Mexico Mexican R/V Puma	Dennis Clark Chuck Trees Bill Broenkow Stan Hooker Ken Voss Howard Gordon	Post-launch certification. Full complement of scientists and measurements.										◇ October or January '94		

Activity Name	Contact(s)	Objectives	1994											
			J	F	M	A	M	J	J	A	S	O	N	D
CalCOFI (Quarterly Cruises)	Gregg Mitchell	Bio-optical algorithm validation.	◇			◇			◇			◇		
Lanai, Hawaii (Possible move to JGOFS site after 2 quarters)	Dennis Clark Bill Broenkow Stan Hooker	Mooring and optical buoy deployment (can be increased in scope).		◇			◇			◇				
Baja, Mexico Mexican R/V Puma	Dennis Clark Chuck Trees Bill Broenkow Stan Hooker Ken Voss Howard Gordon	Post-launch certification. Full complement of scientists and measurements.	◇ January or October '93											
New England Coast (Canadian R/V or NOAA R/V)	Dennis Clark Chuck Trees Jim Mueller Stan Hooker Ken Voss Howard Gordon	Post-launch certification. Full complement of scientists and measurements.				◇								
Mid-Atlantic Bight	Ken Carder Jim Mueller Alan Wiedeman Bob Arnone	Case 1 and 2 pigments, algorithm development and comparisons, validation in high aerosol.					◇	—	◇					
Tasman Sea, Australia	Graham Harris John Parslow	Moored buoy.												
Canary Islands, Spain	Dennis Clark Chuck Trees	Pigments, total bio-optical.						◇	—	◇				
Arabian Sea	Ken Carder Jim Mueller Alan Wiedeman Bob Arnone	Case 1 and 2 pigments, integrate with ONR ARI, coordinate with JGOFS, different Case 2 water.									◇	—	◇	

Fig. 22. Algorithm development field studies in 1991–94 as of October 1991.

exponents for all scenes were 0.1, 0, and 0 for 443, 520, and 550 nm, respectively. These values imply almost no wavelength dependence in aerosol scattering, which is approximately true for marine atmospheres.

2) $L_W(670)$ was assumed to be zero everywhere.
3) The second order interaction between Rayleigh and aerosol scattering was assumed to be zero.
4) The sun glint mask algorithm assumed constant 6 m s^{-1} wind speeds. No radiometric correction was made for sun glint or sea foam.
5) The correction geometry assumed a flat Earth.
6) The Rayleigh optical thickness was assumed to be constant. (In the global processing, the ozone optical thicknesses have been derived from Total Ozone Mapping Spectrometer (TOMS) Dobson units.)
7) The water-leaving radiances were assumed to be independent of scan angle.
8) The water-leaving radiances were assumed to be independent of scan angle.

With the increased SNR and radiometric accuracy and the additional bands in the ultraviolet and near-infrared, the atmospheric correction algorithm will need to remove most, if not all, of these assumptions, if the derived products are to meet the accuracy specifications outlined by the SWG (1.3). Additionally, in order to allow $L_W(670)$ to vary from zero, the Ångström exponents must be extrapolated from the 765 and 865 nm bands to even lower wavelengths (412 nm) than before. How accurately this can be done has not been established. Only assumption 8 can be considered secondary in all cases.

A variable Rayleigh optical thickness requires surface pressure fields and is not a theoretical obstacle, but it does present a problem in obtaining high temporal and spatial resolution estimates of global fields having sufficient accuracy. Similarly, surface winds for the sun glint and foam corrections will be needed. Data sets that have been received from the operational centers, i.e., National Meteorological Center (NMC), Fleet Numerical Oceanography Center (FNOC), and the European Centre for Medium Range Weather Forecasts (ECMWF), have had 12 hour and 2.5° temporal and spatial resolutions. Presumably, higher resolution data is produced and will be made available to the SPO and this possibility will be pursued. Thus, space and time interpolation schemes will need to be developed which take the operational products and estimate fields along the subsatellite track at the required space and time resolutions. This interpolation will need to be performed for every orbit as the satellite progresses through approximately seven orbits between operational product fields. At NASA Headquarters' direction, the SPO will look to the EOS community for help in implementing an operational interpolation algorithm. There are several individuals in the GSFC Earth Sciences Directorate who could assist the SPO in this way.

Howard Gordon, funded under MODIS and the SPO, will have the primary responsibility of providing the operational SeaWiFS atmospheric correction algorithm. Gordon's initial development will focus on the Ångström extrapolation question (pertaining to assumptions 1–3), the Rayleigh-aerosol interactions (assumption 4) and surface roughness effects (assumption 5). Figure 4 illustrates the various radiometric interactions he has proposed for the initial algorithm. Robert Fraser at NASA/GSFC will also be funded to investigate particular problems dealing with topics such as sun glint, Saharan dust, and the Ångström extrapolation problem.

As outlined in the Monterey Workshop proceedings, field observations of the angular distribution of downwelling sky radiance (sensor calibration studies) and spectral atmospheric optical thickness (sensor calibration and bio-optical algorithm studies) are required. The downwelling sky radiance distribution observations require special hardware and will only be collected during certain SeaWiFS sponsored dedicated cruises (at least those conducted by the MODIS team). Also, as with bio-optical data, the SPO will accumulate similar data sets from other sources in order to develop an on-line database for atmospheric algorithm development. The SPO will also solicit from the community independently developed atmospheric correction algorithms so that other techniques and methods can be evaluated. Evaluations would require review of the algorithm's theoretical basis, its computational requirements, and comparison of the operational SeaWiFS derived products with those obtained using other algorithms. This capability will be maintained in-house and processing will be done separately from the operational processing.

Finally, attention must be given to cloud detection. In the CZCS global processing, the only flag used was a fixed value in band 5. Such an algorithm will not be acceptable for SeaWiFS as it does not account for changes in total radiance as a function of solar elevation or for variability in cloud albedo. This problem is being addressed as part of the Pathfinder AVHRR reprocessing. Here the issue is much more complicated in that it requires both daytime and nighttime algorithms. The SPO will work with the SWG in formulating an algorithm for SeaWiFS.

3.6 Field Instrumentation

As emphasized in the Monterey Workshop proceedings, a community-wide program for the standardization of radiometer characterization and calibration must be initiated, especially as the number of investigators collecting data for algorithm development and sensor calibration is expected to grow rapidly during the SeaWiFS era. Some laboratories in the academic community, e.g., CHORS, already have a basic capability under support from on-going projects funded by a combination of NASA, Navy, and

NSF sources. In addition to standardized procedures, digital documentation of calibration results, and radiometer maintenance logs for every instrument, at least those to be used for SeaWiFS algorithm studies, should be filed into a community database. This would provide traceability in data sets, something that is not commonly available in historical data sets. As part of this strategy, the SPO under Bruce Guenther's direction, will support a round-robin calibration of these laboratories' secondary sources. The frequency of routine visits to the laboratories would be based on calibration source usage. Special trips will be needed, for instance, when new equipment is installed that requires certification by the GSFC Standards and Calibration Office (Bruce Guenther, Head).

4. QUALITY CONTROL

SeaWiFS quality control is based on the CZCS quality control system and includes the review of level 1–3 products as well as the input fields used in the derivation of level-2 products. One major difference is that the only ancillary data used in the CZCS processing was historical ozone concentrations derived from the TOMS while SeaWiFS requires other ancillary data received in near real time. Meteorological data analyses will build on what has already been developed within the SEAPAK software package (McClain et al. 1991b).

4.1 Level-1 Screening

Each day, both the recorded LAC and GAC and the High Resolution Picture Transmission (HRPT) LAC received at GSFC will be checked for missing bands and other problems that can be easily recognized by visual means. More analytical tests will include statistical analyses of the radiances, which will be saved in an on-line database. An example would be mean values, after cloud screening, for clear water regions in predefined latitude ranges. Such analyses would provide an indication of changes in the atmosphere and/or in the sensor calibration and will be stored in an online database.

4.2 Level-2 Quality Control

The input fields, as presently identified, are surface wind speed, surface pressure, and ozone concentration. The surface wind and pressure fields will be obtained from the operational meteorology centers. It is well known that these products vary in their accuracies depending on location and on their source. There are a number of studies in the recent literature that evaluate products from the operational centers (NMC, FNOC, and ECMWF), e.g., Toll and Clune (1985) and Trenberth and Olson (1988). The selection of product sources depends on how rapidly they can be received as well as how accurate they are considered to be. Reprocessing of the data using refined calibration and ancillary data fields will be ongoing in parallel with real-time processing and it is conceivable that the various processings will use data from different sources. It is also conceivable that in some processing scenarios, data from different sources will be used in different parts of the world. As with the space and time interpolation problem, the SPO will rely on EOS investigators for direction on what products to use where. Coordination of data transfer from the operational centers will be handled by the SeaWiFS Data System group.

All data will be screened as it is received to identify missing or bad data. In both cases, the interpolation algorithm will need to fill in values at the affected grid points. Also, the data will be compared with climatological data to identify large anomalies. The anomaly fields will be used during the review of level-2 and level-3 products. Also, the analysis software will be capable of extracting time series of wind, pressure, and ozone at any selected location as an aid in determining if observed trends in the derived products are correlated with environmental factors. Correlations can be the result of real processes or artifacts of the processing algorithms. Analyses such as time series at specific locations of interest will be stored on-line and routinely updated.

4.3 Level-2 Product Screening

All level-1 recorded LAC and HRPT LAC data captured at GSFC will be processed to level-2 and reviewed. For scenes routinely sampled at LAC resolution, e.g., the Hawaii optical mooring site and the U.S. East Coast, statistical analyses of the level-2 fields will be performed and saved in an on-line database. Analysis products will include geometric and arithmetic mean values for clear water regions. In cases where the LAC coverage was collected in support of field projects, the level-2 data will be saved and, when possible, transmitted to the research vessel(s). Also, the extraction of the satellite data for comparison with buoy data mentioned in Section 3.4 could be performed during this procedure.

All level-2 GAC derived products will be reviewed in a manner similar to the CZCS quality control scenario, but with refined rejection criteria (see Fig. 7). In the CZCS quality control procedure, a daily composite of four derived products (pigment concentration, $L_A(670)$, $L_{WN}(443)$, and $L_{WN}(550)$ was reviewed. The procedure allowed the user to sequence through the day's coverage scene by scene and accept or reject the scene. If a scene was rejected, a list of rejection criteria was presented and one selected with optional comments. This information was passed to the processing database and was used in identifying scenes to be excluded from the level-3 products and was also included in the CZCS browse system.

Several improvements in this system have been discussed including the incorporation of masks that use quantitative criteria to identify questionable data and the ability to flag portions of scenes for rejection without rejecting entire scenes. For example, the "Dubious Water Radiance" and "Other" categories shown in Fig. 7 would be replaced with more explicit radiometric tests. The definition of these criteria will be based on analyses of field data in the SPO databases and on the recommendations of the SWG and other investigators. For example, much radiometric data from coccolithophore blooms have been collected in recent field studies that could be used in developing a coccolithophore flag. Also, with the additional near-infrared bands, it may be possible to flag regions where dust is the dominant aerosol. One difference in how quality control will be executed lies in the fact that SeaWiFS data will not be packaged into discrete two minute scenes, as were the CZCS data, and there will not be duplicate copies of the data.

4.4 Level-3 Product Screening

The level-3 products represent composites of fields averaged over a number of time scales (weekly, monthly, annually). These products will be reviewed as they are produced. Often problems missed during the daily review of level-2 products can be identified in the level-3 fields. The monthly composites of CZCS pigment were reviewed as they were produced, and, in most cases, bad data had been approved during the initial quality control. In those cases, a second pass through the level-2 products was required in order to identify the specific problem scenes. Analyses of the mean fields, such as mean pigment concentration in clear water regimes, will be stored in an on-line database. These time series will indicate long-term trends in the products, which can be correlated with calibration data (solar, lunar, and vicarious), to determine if trends in the derived products are artifacts of the calibration. These products could also be compared with other diagnostic fields such as mean Ekman upwelling velocities derived from the wind fields (McClain et al. 1990). Such tests would provide additional insights as to how well the system and algorithms were performing.

APPENDICES

A. Radiometric specifications for SeaWiFS. December 11, 1991 memo from Bob Barnes to Wayne Esaias.
B. SeaWiFS bio-optical data distribution policy.
C. Considerations on SeaWiFS Lunar Observations. July 9, 1991 memo from Bob Barnes to Wayne Esaias.

Appendix A

December 11, 1991

TO: Wayne Esaias
FROM: Bob Barnes
SUBJECT: Gains for the SeaWiFS Critical Design Review
REFERENCE:

1) Memo from Bob Barnes to Wayne Esaias, dated 6/28/91.
2) Fax from Hugh Kieffer to Bob Barnes, dated 7/31/91.
3) E-Mail message from Howard Gordon to SeaWiFS Project Office, dated 11/13/91.
4) Memo from Bob Barnes to Wayne Esaias, dated 12/5/91.
5) Memo from Bob Barnes to Wayne Esaias, dated 8/20/91.

Since my zeroth order calculations of the lunar radiances for SeaWiFS (Ref. 1), we have received improved estimates of these radiances from Hugh Kieffer (Ref. 2) and from Howard Gordon (Ref. 3). More recently, we have calculated corrections to the science, lunar, and solar radiances at the new wavelengths for channels 4, 5, and 6 (Ref. 4). In addition, we have looked at the radiances from "super" blooms of coccolithophores. We decided not to modify the science gains to insure that there will be no saturation of the instrument by these blooms, since we feel that coccolithophore blooms with reflectances up to about 20 percent can be handled by the existing science gains (Ref. 4). Based on this background information, we can now tabulate the new sets of expected input radiances for SeaWiFS.

Table A-1. Revised radiometric specifications for SeaWiFS.

Wavelength	Saturation Radiance	Input Radiance	SNR	Comments
402–422	13.63	9.10	499	
433–453	13.25	8.41	674	
480–500	10.50	6.56	667	
500–520	9.08	5.64	640	Rev.
545–565	7.44	4.57	596	Rev.
660–680	4.20	2.46	442	Rev.
745–785	3.00	1.61	455	
845–885	2.13	1.09	467	

Wavelength is in units of nanometers.
Radiance is in units of $\mathrm{mW\,cm^{-2}\,\mu m^{-1}\,sr^{-1}}$.

The revised radiances at 500–520, 545–565, and 660–680 nm are 4% higher, 3% higher, and 1% lower than the original values, respectively. The set of saturation radiances in Table 1 can be compared with the expected saturation radiances from the lunar and solar measurements. The lunar and solar radiances were derived from Howard Gordon's calculations in Ref. 3.

Table A-2. Expected saturation radiances for the lunar and solar measurements.

Wavelength	Saturation Rad. (Lunar)	Gain	Saturation Rad. (Solar)	Gain
402–422	6.78	2.01	6.82	2.00
433–453	7.61	1.74	7.53	1.76
480–500	8.75	1.20	7.78	1.35
500–520	9.11	1.00	7.42	1.22
545–565	9.67	0.77	7.40	1.01
660–680	9.04	0.46	6.07	0.69
745–785	9.38	0.32	4.92	0.61
845–885	8.19	0.26	3.87	0.55

Gain is the gain required to change these saturation radiances to the saturation radiances in Table A-1.

For SeaWiFS, there is a second science gain (gain of 2) that will account for the predicted decrease in sensitivity of the instrument. An examination of Table A-2 shows some duplications with gains from the science channels and some duplications between the lunar and solar gains. As a result, we have devised gains that will account for the needs of the measurements and some new intermediate gains that fall between the science gains of 1 and 2. The gains in this memorandum are nearly identical with those recommended by Howard Gordon in Ref. 3. These gains are also very similar to those in Table A-3 of Ref. 5, which was submitted to the Santa Barbara Research Center last August, so that they could start the rough setting of the instrument. The following tables have been set up for easy comparison with the values previously sent to SBRC.

Table A-3. Multiplicative factors for the four SeaWiFS gains relative to gain 1 saturation radiances.

Wavelength	Gain 1	Gain 2	Gain 3	Gain 4
402–422	1.00	2.00(1,2)	1.70	1.30
433–453	1.00	2.00	1.70(1,2)	1.30
480–500	1.00	2.00	1.25(1,2)	1.70
500–520	1.00(1)	2.00	1.70	1.25(2)
545–565	1.00(2)	2.00	0.77(1)	1.60
660–680	1.00	2.00	0.46(1)	0.70(2)
745–785	1.00	2.00	0.32(1)	0.61(2)
845–885	1.00	2.00	0.26(1)	0.55(2)

(1) = gain used for lunar measurements.
(2) = gain used for solar measurements.

Table A-4. Saturation radiances for the four SeaWiFS gains.

Wavelength	Gain 1	Gain 2	Gain 3	Gain 4
402–422	13.63	6.82	8.02	10.48
433–453	13.25	6.63	7.79	10.19
480–500	10.50	5.25	8.40	6.18
500–520	9.08	4.54	5.34	7.26
545–565	7.44	3.72	9.66	4.65
660–680	4.20	2.10	9.13	6.00
745–785	3.00	1.50	9.38	4.92
845–885	2.13	1.07	8.19	3.87

Appendix B

SeaWiFS Bio-optical Data Distribution Policy

(Subject to Revision)

12/16/91

This policy covers data submitted to the National Aeronautics and Space Administration (NASA) SeaWiFS Project Office (SPO) at Goddard Space Flight Center (GSFC) for inclusion in the calibration and validation data collection. Its purpose is to ensure that accurate *in situ*, shipboard and airborne bio-optical measurements are made rapidly available to the Science Team (ST) members (and other approved investigators) for advanced algorithm development and data product validation purposes, while ensuring that the observer or provider receives proper credit and acknowledgement for the considerable expertise and effort applied to obtaining and reducing the data.

SUBMISSION: Ocean color algorithm development is essentially observation limited, and rapid turnaround and access to such data is crucial for progress. Data obtained under contract should be submitted as soon as proper calibration information can be applied, and not later than 6 months from collection. Science Team members and other investigators making suitable observations are encouraged to provide their data as soon as possible. Data is expected to be submitted no later than one year following collection, or at the time of submission of any paper using the data by the provider. Investigators who make observations of bio-optical parameters are expected to submit their observations prior to accessing data from others.

DATA ACCESS: Access to the digital data will be limited initially to approved users as determined by the ST and the providers, for a period of one year following collection. Other investigators interested in obtaining such data will be referred to the provider for permission. Following an agreed upon period data will be deemed public, and access will be unlimited. Records of distribution will be maintained and forwarded to the provider, and citation requirements set forth below still apply. Only information about the digital data (parameters, locations, dates, investigators, etc.) will be available for unlimited downloading or distribution.

CONDITIONS ON DATA UTILIZATION: Users of data will be required to provide proper credit and acknowledgement of the provider. At minimum, this should be acknowledgement by name and citation of any works describing the data or its use. Citation should also be made of the data archive. Users of data are encouraged to discuss relevant findings with the provider early in the research. The user is required to give to all providers of the data of which he has made use, a copy of any manuscript resulting from use of the data, prior to or coincident with initial submission for publication. Within one year of data collection, the provider(s) shall be offered the right to be a named co-author.

UPDATES AND CORRECTIONS: A major purpose of the data base is to facilitate comparisons of absolute calibrations and protocols between *in situ* observations (regionally, temporally, by technique, by investigator, etc.), as well as between *in situ* and remotely sensed observations. Updates and corrections to submitted data sets by the provider are encouraged. Records will be maintained of updates and corrections, summaries of updates will be posted on a database board, and users shall be notified of the updates. The methodology for doing this efficiently will probably have to be developed on a case by case basis. The current data in the archive should be identical with the data used in the provider's most recent publications or current research.

FORMATS: Data should be provided in an agreed upon format, along with relevant information describing collection conditions, instrument performance and calibration, and statements of its accuracy. In general, parameters and units shall be as described in the Monterey Calibration and Validation Workshop report, and recommended format is to be determined. Data values shall be in their final form (e.g., providing volts together with conversion coefficients and drifts is unacceptable). High level data sets are encouraged, e.g., normalized water-leaving radiance spectra, together with descriptions and/or citations of procedures used to derive the values. Data should be segmented into rational sets, by station, date, parameter, etc. Data quality, calibration traceability and history, drift, and sampling protocols may be in text format. Listing of what criteria need to be treated should be developed by the ST.

RECORD KEEPING: The SPO will maintain an accurate data base of these data. All data will retain the investigator's identification, and any necessary quality control information, at the level of distribution. This necessitates that combined data sets from several investigators retain their individual identifications, if any such combining is done by the SPO. The SPO will maintain accurate records of distribution, and will inform the original provider of investigators requesting their data. The data will not be released for inclusion in other data bases which do not agree to honor conditions set forth above.

Appendix C

July 9, 1991

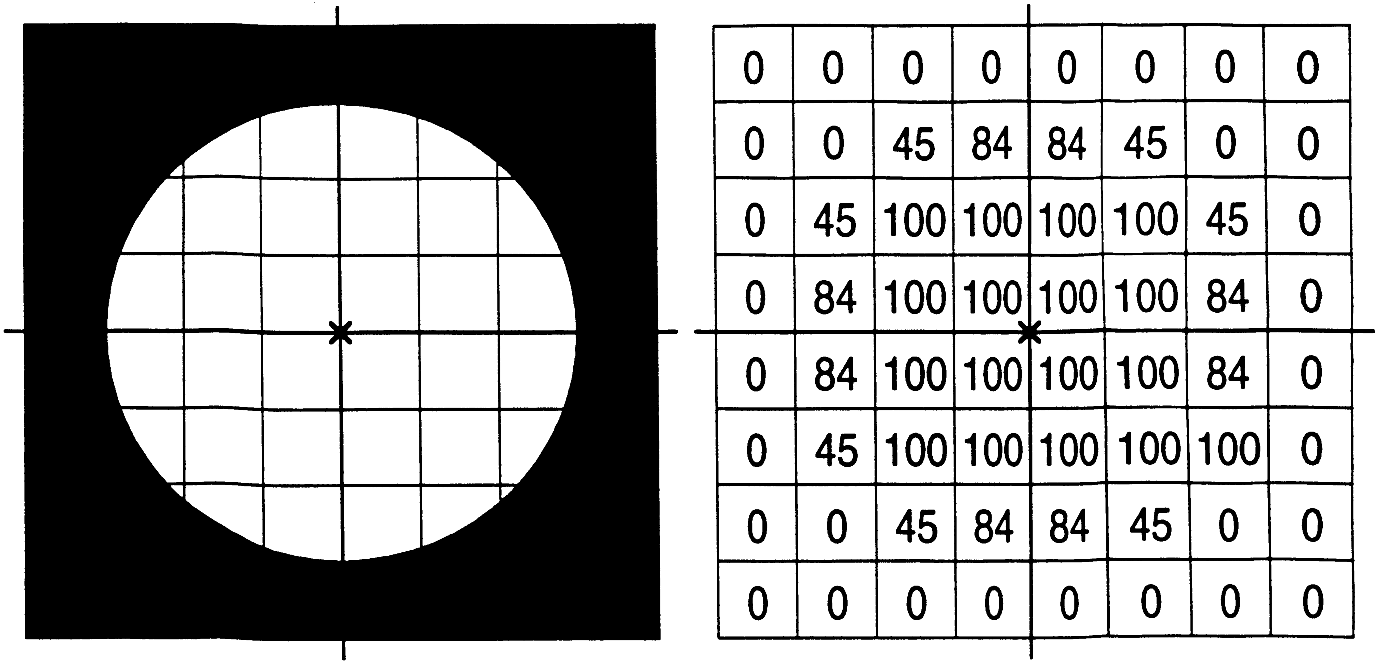
TO: Wayne Esaias
FROM: Bob Barnes
SUBJECT: Thoughts on SeaWiFS Calibrations

1. LUNAR DIAMETER. In terms of the SeaWiFS angular resolution, the moon is just under 6 pixels wide. Figure C-1 shows the moon in terms of MODIS-T pixels, which are 1.56 mrad wide (compared with the SeaWiFS 1.60 mrad). For a swath across the center of the moon there will be one partially illuminated pixel, followed by 4 fully illuminated ones. Overall, the width of the moon is just over 1/2 of the 10 pixel response time (bright to dark) for the instrument as per the SeaWiFS specifications. It remains an open question whether SeaWiFS has a sufficiently fast response time to see the moon well enough for calibration purposes.
2. DIFFUSER DEGRADATION RATE. It is my understanding that the Landsat diffuser degraded to the point of uselessness in a few days. This was also true of the diffuser on the Nimbus 4 BUV, which was useless after a week. However, the diffuser on the Nimbus 7 SBUV was stored in a protected position, and it has lasted for several years. The same is true of the diffuser on the NOAA 9 SBUV/2. The degradation rate for the SeaWiFS diffuser will determine its deployment scheme without regard to the plans that we make.
3. A STRAW-MAN PLAN FOR DIFFUSER AND LUNAR CALIBRATIONS. This plan assumes diffuser degradation of about 10measurements over a 5-year lifetime. Semi-annual lunar observations will give 10 measurements over the same period. More frequent observations will improve the statistics of these long term measurements. However, an increased number of diffuser deployments can increase the diffuser's degradation, and more frequent lunar measurements increase the risks associated with changes in the rotation rate of the spacecraft. Were the diffuser to become useless (due to rapid degradation) then quarterly lunar observations might become necessary to check instrument changes. Initial diffuser and lunar measurements must be made soon after the completion of spacecraft outgassing. These initial measurements will give the baseline for the long-term sets of calibrations.
4. STANDARD SeaWiFS PLATFORM ROTATION RATE. Preliminary calculations of mine show an orbital period of 98.7 min (5920 sec) for SeaWiFS. This gives the platform a rotation rate of 1.06 mrad/sec to maintain pointing toward the Earth's center. During viewing the Earth, of course, the surface scans along track under the nadir-pointing instrument. For the moon the along track scan comes from the rotation rate of the SeaWiFS platform, itself.
5. A STRAW-MAN PLATFORM ROTATION PLAN FOR VIEWING OF THE MOON. At an equatorial crossing on the dark side of the Earth cut the rotation rate of the platform to 1/2 of the standard rate. On the second dark side equatorial crossing that follows return the rotation rate to normal. At the intermediate dark side crossing SeaWiFS will point toward the moon.
    a. The instrument will point 45 degrees or more from the Sun on the illuminated side of the Earth. The use of 20 degree fore and aft pointing can increase this angular difference. The danger of exposing the instrument optics to the sun should be eliminated in this manner.
    b. The rotation rate of the platform would be 0.53 mrad/sec. For the 4 pixel (6.4 mrad) central area of the moon (see Fig. C-1) and this along track rotation rate, the scan time would be 12 sec. This would include 72 across track scans of the instrument telescope.
    c. This technique will remove two consecutive measurement orbits by the instrument. However, if this is done twice a year, the loss of data is minimal. I assume that these considerations will have to be addresssed in meetings with OSC.

Regards,

GLOSSARY

ACRIM	Active Cavity Radiometer Irradiance Monitor
A/D	Analog-to-Digital
ADEOS	Advanced Earth Observation Satellite
AT	Along-Track
AVHRR	Advanced Very High Resolution Radiometer
BBR	Band-to-Band Registration
bpi	bits per inch
BRDF	Bidirectional Reflectance Distribution Function
BUV	Backscatter Ultraviolet Spectrometer



0	0	0	0	0	0	0	0
0	0	45	84	84	45	0	0
0	45	100	100	100	100	45	0
0	84	100	100	100	100	84	0
0	84	100	100	100	100	84	0
0	45	100	100	100	100	100	0
0	0	45	84	84	45	0	0
0	0	0	0	0	0	0	0

Fig. C-1. A View of the Full Moon in Terms of Pixels. For SeaWiFS the pixel size is 1.60×1.60 mrad, equivalent to the pixel size in this figure.

CalCOFI	California Cooperative Fisheries Institute
Cal/Val	Calibration and Validation
Case 1	Water whose reflectance is determined solely by absorption.
Case 2	Water whose reflectance is significantly influenced by scattering.
cpu	Central Processing Unit
CDR	Critial Design Review
CHORS	Center for Hydro-Optics and Remote Sensing (San Diego State University)
CRM	Contrast Reduction Meter
CRT	Calibrated Radiance Tapes
CRT	Cathode Ray Tube Display
CT	Cross-Track
CTD	Conductivity, Temperature, and Depth
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DC	Direct Current
DCP	Data Collection Platform
ECMWF	European Centre for Medium Range Weather Forecasts
$E_d(z,\lambda)$	Downwelled spectral irradiance
EOS	Earth Observing Satellite
EOSAT	Earth Observation Satellite Company
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Sensor
ER-2	Earth Resources-2
FWHM	Full-Width Half-Maximum
FNOC	Fleet Numerical Oceanography Center

GAC	Global Area Coverage, coarse resolution satellite data with a nominal ground resolution of approximately 4 km.
GLI	Global Imager
GOES	Geosynchronous Orbital Environmental Satellite
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HPLC	High Performance Liquid Chromatography
HRPT	High Resolution Picture Transmission
HYDRA	Hydrographic Data Reduction and Analysis
IFOV	Instantaneous Field of View
I/O	Input/Output
IR	Infrared
JGOFS	Joint Global Ocean Flux Study
K	Diffuse attenuation coefficient (at 490 nm: $K(490)$
LAC	Local Area Coverage, fine resolution satellite data with a nominal ground resolution of approximately 1 km.
Level-0	Raw data.
Level-1	Calibrated radiances.
Level-2	Derived products.
Level-3	Gridded and averaged derived products.
$L_u(z,\lambda)$	Upwelled spectral radiance
L_W	Water-leaving radiance (at 520 nm: $L_W(520)$).
L_{WN}	Normalized water-leaving radiance (at 550 nm: $L_{WN}(550)$).

MAREX	Marine Resources Experiment Program
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Image Spectrometer
MODIS-N	Moderate Resolution Image Spectrometer—Nadir
MODIS-T	Moderate Resolution Image Spectrometer—Tilt
MTF	Modulation Transfer Function
NASA	National Aeronautics and Space Administration
NEΔT	Noise Equivalent Delta Temperature
NEδL	Noise Equivalent delta Radiance
NET	Nimbus Experiment Team
NIST	National Institute of Standards of Technology
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NRA	NASA Research Announcement
NSF	National Science Foundation
OCTS	Ocean Color Temperature Sensor (Japan)
ONR	Office of Naval Research
OSC	Orbital Sciences Corporation
PDR	Preliminary Design Review
PIKE	Phased Illuminated Knife Edge
QC	Quality Control
RDF	Radio Direction Finder
ROSIS	Remote Sensing Imaging Spectrometer, also known as the Reflective Optics System Imaging Spectrometer (Germany)
RTOP	Research and Technology Operation Plan
R_z	Sunspot Number
S	Solar Constant
SBRC	Santa Barbara Research Center (Hughes)
SBUV	Solar Backscatter Ultraviolet Radiometer
SBUV–2	Solar Backscatter Ultraviolet Radiometer–2
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SIS	Spherical Integrating Source
SISSR	Submerged *In Situ* Spectral Radiometer
SMM	Solar Maximum Mission
SNR	Signal-to-Noise Ratio
SPO	SeaWiFS Project Office
SPSWG	SeaWiFS Prelaunch Science Working Group
SST	Sea Surface Temperature
ST	Science Team
SWG	Science Working Group
TBD	To Be Determined
TOMS	Total Ozone Mapping Spectrometer
VHF	Very High Frequency
VISNIR	Visible and Near Infrared
WORM	Write Once Read Many

References

Abbott, M.R., and D.B. Chelton, 1991: Advances in passive remote sensing of the ocean, in: *U. S. National Report to International Union of Geodesy and Geophysics 1987–1990, Contributions in Oceanography.* Am. Geophys. Union, 571–589.

Abel, P., B. Guenther, R. Galimore, and J. Cooper, 1991: Calibration results for NOAA-11 AVHRR channels 1 and 2 from congruent aircraft observations. (in preparation).

——, G.R. Smith, R.H. Levin, and H. Jacobowitz, 1988: Results from aircraft measurements over White Sands, New Mexico, to calibrate the visible channels of spacecraft instruments. *SPIE*, **924,** 208–214.

Austin, R.W., Gulf of Mexico, 1980: Ocean-color surface-truth measurements. *Boundary-Layer Meteor.,* **18,** 269–285.

——, and T.J. Petzold, 1981: The determination of diffuse attenuation coefficient of sea water using the Coastal Zone Color Scanner. *Oceanography from Space,* J.F.R. Gower, Ed., Plenum Press, 239–256.

Balch, W.M., R. Evans, J. Brown, G. Feldman, C. McClain, and W. Esaias, 1991: The remote sensing of ocean primary productivity—use of a new data compilation to test satellite algorithms. *J. Geophys. Res.,* (submitted).

Ball Aerospace Systems Division, 1979: Development of the Coastal Zone Color Scanner for Nimbus 7, Test and Performance Data, *Final Report F78-11, Rev. A, Vol. 2* Boulder, CO, 94 pp.

Burlov-Vasiljev, K.A., E.A. Gurtovenko, and Y.B. Matvejev, 1991: The Solar Radiation Between 310–680 nm. *SOLARS-22 Conference Proceedings,* Boulder, CO, (in preparation).

Clark, D.K., E.T. Baker, and A.E. Strong, 1980: Upwelled spectral radiance distributions in relation to particulate matter in sea water. *Boundary-Layer Meteor.,* **18,** 287-298.

——, 1981: Phytoplankton algorithms for the Nimbus-7 CZCS. *Oceanography from Space,* J.R.F. Gower, Ed., Plenum Press, 227–238.

Denman, K.L., and M.R. Abbott, 1988: Time evolution of surface chlorophyll patterns from cross spectrum analysis of satellite color images. *J. Geophys. Res.,* **93,** 6,789–6,798.

Esaias, W.E., G. Feldman, C.R. McClain, and J. Elrod, 1986: Satellite observations of oceanic primary productivity. *EOS Trans. AGU,* **67,** 835–837.

Feldman, G., N. Kuring, C. Ng, C. McClain, J. Elrod, N. Maynard, D. Endres, R. Evans, J. Brown, S. Walsh, M. Carle, and G. Podesta, 1989: Ocean color: availability of the global data set. *EOS Trans. AGU,* **70,** 634.

Gordon, H.R., D.K. Clark, J.L. Mueller, and W.A. Hovis, 1980: Phytoplankton pigments from the Nimbus-7 Coastal Zone Color Scanner: Comparisons with surface measurements, *Science,* **210,** 63-66.

——, 1981: Reduction of error introduced in the processing of coastal zone color scanner-type imagery resulting from sensor calibration and solar irradiance uncertainty. *Appl. Opt.,* **20,** 207–210.

——, and D.K. Clark, 1981: Clear water radiances for atmospheric correction of coastal zone color scanner imagery. *Appl. Opt.,* **20,** 4,175–4,180.

——, D.K. Clark, J.W. Brown, O.B. Brown, R.H. Evans, and W.W. Broenkow, 1983a: Phytoplankton pigment concentrations in the Middle Atlantic Bight: Comparison of ship determinations and CZCS estimates, *Appl. Opt.,* **22,** 20-36.

——, J.W. Brown, O.B. Brown, R.H. Evans, and D.K. Clark, 1983b: Nimbus 7 CZCS: reduction of its radiometric sensitivity with time. *Appl. Opt.,* **24,** 3,929–3,931.

——, 1987: Visible calibration of ocean-viewing sensors. *Remote Sens. of Environ.,* **22,** 103–126.

——, and D.J. Castaño, 1987: Coastal Zone Color Scanner atmospheric correction algorithm: multiple scattering effects. *Appl. Opt.,* **26,** 2,111–2,122.

——, J.W. Brown, and R.H. Evans, 1988: Exact Rayleigh scattering calculations for use with the Nimbus-7 Coastal Zone Color Scanner. *Appl. Opt., 27,* **5,** 862-871.

——, 1990: Radiometric considerations for ocean color remote sensors. *Appl. Opt.,* **29,** 3,228–3,236.

Guenther, B., 1991: Accuracy and precisions actually achieved for large aperture sources for aircraft and space investigations. *Metrologia,* **28,** 229–232.

Hay, B.J., C.R. McClain, and M. Petzold, 1991: Phytoplankton pigment assessment in the Arabian Sea comparing satellite data and *in situ* data. *Remote Sens. of Environ.,* (submitted).

Hovis, W.A., D.K. Clark, F. Anderson, R.W. Austin, W.H. Wilson, E.T. Baker, D. Ball, H.R. Gordon, J.L. Mueller, S. El-Sayed, B. Sturm, R.C. Wrigley, and C.S. Yentsch, 1980: Nimbus-7 Coastal Zone Color Scanner: System description and initial imagery. *Science,* **210,** 60–63.

——, 1981: The Nimbus-7 Coastal Zone Color Scanner (CZCS) program. *Oceanography from Space,* J.R.F. Gower, Ed., Plenum Press, 213–225.

——, J.S. Knoll, and G.R. Smith, 1985: Aircraft measurements for calibration of an orbiting spacecraft sensor, *Appl. Opt.* **24,** 407–410.

Joint EOSAT/NASA SeaWiFS Working Group, 1987: *System Concept for Wide-Field-of-View Observations of Ocean Phenomena from Space.* E.S. Putnam, Ed., Earth Observation Satellite Co., Lanham, MD, 92 pp.

McClain, C.R., W.E. Esaias, G.C. Feldman, J. Elrod, D. Endres, J. Firestone, M. Darzi, R. Evans, and J. Brown, 1990: Physical and biological processes in the North Atlantic during the First Global GARP Experiment. *J. Geophys. Res.,* **95,** 18,027–18,048.

——, G. Feldman, and W. Esaias, 1991a: A review of the Nimbus-7 Coastal Zone Color Scanner data set and remote sensing of biological oceanic productivity. *Global Change Atlas,* C. Parkinson, J. Foster and R. Gurney, Eds., Cambridge University Press, (in press).

——, M. Darzi, J. Firestone, E.-N. Yeh, G. Fu, and D. Endres, 1991a: SEAPAK Users Guide, Version 2.0, Vol. I—System Description, *NASA Tech. Mem. 100728,* 158 pp.

——, ——, ——, ——, ——, and ——, 1991b: SEAPAK Users Guide, Version 2.0, Vol. II—Descriptions of Programs. *NASA Tech. Mem. 100728,* 586 pp.

Mecherikunnel, A.T., and H.L. Kyle, 1991: Eleven-year cycle of solar constant variation from spacecraft measurements: 1978 to 1990. *Science,* (submitted).

Mitchell, B.G., and O. Holm-Hansen, 1991: Bio-optical properties of Antarctic Peninsula waters: differentiation from temperate ocean models, *Deep-Sea Res., 39,* **8/9,** 1,009-1,028.

Morel, A., and L. Prieur, 1977: Analysis of variations in ocean color. *Limnol. Oceanogr.,* **22,** 709–722.

——, 1980: In-water and remote measurements of ocean color, *Bound.-layer Meteorology.,* **18,** 178–201.

Mueller, J.L., 1985: Nimbus-7 CZCS: confirmation of its radiometric sensitivity decay rate through 1982. *Appl. Opt.,* **24,** 1,043–1,047.

——, 1988: Nimbus-7 CZCS: electronic overshoot due to cloud reflectance. *Appl. Opt.,* **27,** 438–440.

——, and R.W. Austin, 1992: Ocean optics protocols. *NASA Tech. Memo. 104566, Vol. 5,* S.B. Hooker and E.R. Firestone, Eds., 45 pp.

Muller-Karger, F.E., C.R. McClain, R.N. Sambrotto, and G.C. Ray, 1990: A comparison of ship and CZCS-mapped distributions of phytoplankton in the Southeastern Bering Sea. *J. Geophys. Res.,* **95,** 11,483–11,499.

National Aeronautics and Space Administration, 1982: The Marine Resources Experiment Program (MAREX). *Report of the Ocean Color Science Working Group,* NASA/Goddard Space Flight Center, Greenbelt, MD, 107 pp.

Neckel, H., and D. Labs, 1984: The solar radiation between 3300 and 12500 Å. *Sol. Phys.,* **90,** 205–258.

Reynolds, R.W., 1988: A real-time global sea surface temperature analysis. *J. Climate,* **1,** 75–86.

Smith, R.C., and W.H. Wilson, 1981: Ship and satellite bio-optical research in the California Bight. *Oceanography from Space,* J.F.R. Gower, Ed., Plenum Press, 281–294.

Toll, R.F., Jr., and W.M. Clune, 1985: An operational evaluation of the Navy Operational Global Atmospheric Prediction System (NOGAPS): 48-hour surface pressure forecasts. *Mon. Weather Rev.,* **113,** 1,433–1,440.

Trenberth, K.E., and J.G. Olson, 1988: An evaluation and intercomparison of global analyses from the National Meteorological Center and the European Centre for Me-dium Range Weather Forecasts. *Bull. Am. Meteor. Soc.,* **69,** 1,047–1,057.

Viollier, M., 1982: Radiance calibration of the Coastal Zone Color Scanner: a proposed adjustment. *Appl. Opt.,* **21,** 1,142–1,145.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1992

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
SeaWiFS Technical Report Series
Volume 3–SeaWiFS Calibration and Validation Plan

5. FUNDING NUMBERS
Code 970.2

6. AUTHOR(S)
Charles R. McClain, Wayne E. Esasias, William Barnes, Bruce Guenther,
Daniel Endres, Stanford B. Hooker, B. Greg Mitchell, and Robert Barnes
Series Editors: Stanford B. Hooker and Elaine R. Firestone

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Laboratory for Hydrospheric Processes
Goddard Space Flight Center
Greenbelt, Maryland 20771

8. PERFORMING ORGANIZATION REPORT NUMBER
92B00117

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TM–104566, Vol. 3

11. SUPPLEMENTARY NOTES
B.G. Mitchell: NASA Headquarters, Washington, DC; R. Barnes: CHEMAL, Inc, Wallops Island, VA;
E.R. Firestone: General Sciences Corporation, Laurel, Maryland.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 48
Report is available from the Center for AeroSpace Information (CASI),
7121 Standard Drive, Hanover, MD 21076–1320; (301)621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) will be the first ocean color satellite since the Nimbus-7 Coastal Zone Color Scanner (CZCS), which ceased operation in 1986. Unlike the CZCS, which was designed as a proof-of-concept experiment, SeaWiFS will provide routine global coverage every two days and is designed to provide estimates of photosynthetic pigment concentrations of sufficient accuracy for use in quantitative studies of the ocean's primary productivity and biogeochemistry. A review of the CZCS mission is included that describes the limitations of that data set and provides justification for a comprehensive SeaWiFS calibration and validation program. To accomplish the scientific objectives of the mission, the sensor's calibration must be constantly monitored, and robust atmospheric correction and bio-optical algorithms must be developed. The plan incorporates a multi-faceted approach to sensor calibration using a combination of vicarious (based on *in situ* observations) and onboard calibration techniques. Because of budget constraints and the limited availability of ship resources, the development of the operational algorithms (atmospheric and bio-optical) will rely heavily on collaborations with the Earth Observing Satellite (EOS), the Moderate Resolution Imaging Spectrometer (MODIS) oceans team, and projects sponsored by other agencies, e.g., the United States Navy and the National Science Foundation (NSF). Other elements of the plan include the routine quality control of input ancillary data (e.g., surface wind, surface pressure, ozone concentration, etc., used in the processing and the verification of the level-0 (raw) data to level-1 (calibrated radiances), level-2 (derived products) and level-3 (gridded and averaged derived data) products.

14. SUBJECT TERMS
Oceanography, SeaWiFS, CZCS, Coastal Zone Color Scanner, Calibration/
Validation, Sensor, Algorithm Development, Quality Control

15. NUMBER OF PAGES
43

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18, 298-102