Oceanographic Bio-Optical Profiling System II

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ABSTRACT

A second generation Bio-Optical Profiling System (BOPS) has been designed, built and used extensively at sea. The BOPS-II is an oceanographic instrument used to measure in-water optical, biological and physical properties in support of interdisciplinary programs. Significant advances beyond BOPS-I include: a depth capability of 500 m; more rapid data acquisition for higher water column resolution; lower inherent dark signal giving greater sensitivity; and greater multicomponent capability, permitting a wide range of additional sensors. The BOPS-II has a proven record of reliability supporting sampling strategies using ship, mooring, aircraft, and satellite optical sensors for ocean research. Rather than an article about a newly designed instrument, this is a report of an instrument and its optical calibration that has been used routinely for nearly a decade, often in the most extreme environments of the world's oceans. An example of optical calibration history is included since calibrations are among the most important aspects of ocean optical measurements, whether in support of a single field experiment or of long-term data collection. The BOPS instrument has served as a model for new generations of optical profiling sensors.

Keywords: optical, ocean color, instrumentation, long-term, time-series

1. INTRODUCTION

Oceanographic Bio-Optical Profiling Systems (BOPS) have been used for over a decade in support of interdisciplinary ocean research. The BOPS[1] was originally designed to: (1) permit the rapid acquisition of data so as to accommodate shipboard "synoptic" sampling, (2) provide an instrument platform for interdisciplinary sampling using ancillary instrumentation, and (3) measure parameters necessary for bio-optical and satellite ocean color research. As used here, interdisciplinary (optics, physics, chemistry, biology) sampling implies close coupling and a common scientific focus for each discipline as distinct from multidisciplinary where frequently samples taken for each discipline are separated in space and/or in time. The BOPS-II design builds upon the original philosophy but makes use of recent technical advances to significantly enhance at sea performance.

Bio-optics is a term coined[2] to represent the mechanistic coupling of dissolved and suspended biogenetic material in ocean waters and corresponding ocean optical properties. Given concentrations of these materials, optical properties can be estimated (direct problem) or conversely, ocean optical properties can be used to infer constituents and concentrations of biogenetic material within the water column (indirect problem) [3]. The use of optical sensors to determine proxy estimations of pigment biomass and phytoplankton production is now widely accepted in oceanography where optical sensors have been deployed on a variety of platforms (ships, moorings, aircraft, satellites). Bio-optical techniques are increasingly important for studies aimed at advancing our understanding of global ocean processes since they permit sampling of biological parameters over space and time scales that would otherwise be impracticable[4].

The Joint Ocean Flux Study (JGOFS) is one recent example of an international, interdisciplinary research project with a global perspective. The long-range goals of JGOFS are: "1) To evaluate and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and 2) To develop the capability to predict the response of oceanic biogeochemical processes to climate change" [5]. A common theme of JGOFS and related studies is to understand the processes and controls governing phytoplankton production and the fate of related biogenic materials in the sea. Bio-optical processes are a recognized component of such research because only satellite observations permit global coverage [4,6].

Oceanographic time series programs such as the Hawaii Ocean Time-series (HOT)[7], Bermuda Atlantic Time-series Study (BATS)[8], and the Palmer Long-Term Ecological Research (Palmer LTER)[9] are examples of programs designed to gain a comprehensive understanding of habitat variability in key locations and to provide the long-term observations necessary to put human induced change into perspective with respect to natural variability. Optical observations play an important role in these long-term programs by permitting rapid proxy estimation of biological parameters, and BOPS-like instruments have been used in both BATS and Palmer LTER as routine water column profiling instruments. In addition, the Palmer LTER BOPS-II rosette provides twelve 5 or 12 liter 'clean' water samples for biological and chemical analysis.

High quality optical surface data, in conjunction with the next generation of ocean color satellite sensors (e.g., SeaWiFS, OCTS, MODIS, etc.) [10], will provide proxy estimation of pigment biomass across a range of space/time scales and with a higher accuracy than would otherwise be possible. SeaWiFS workshops and proceedings [11-14] have detailed science objectives and requirements for contemporaneous surface calibration/validation and bio-optical algorithm development for the SeaWiFS and related ocean color projects. Mueller and Austin (Table 1) [14] present a summary of these requirements. The BOPS-II was designed to complement ocean color satellite observations and operate within the optics protocols necessary to optimize the usefulness of SeaWiFS data. Table 1 summarizes the SeaWiFS requirements which can be met using the BOPS-II.

Related scientific objectives influencing the design and construction of optical profiling systems include: the quantitative description and predictive modeling of upper ocean radiant energy balance; the description and prognostic modeling of the coupling between physical forcing and the dynamics of chlorophyll variation; and the description and modeling of ocean optical variability as a function of relevant physical and biological processes. These efforts require bio-optical characterization of large ocean areas.

In addition to the scientific objective of acquiring data synoptically from multiple platforms, there are operational constraints imposed by the interdisciplinary nature of oceanographic programs which define requirements for a BOPS-like instrument. These criteria include: 1) rapid measurement of important optical, biological and physical parameters to accommodate limited ship-board "wire time"; 2) compatibility of the data acquisition system with conventional cables and winches of the oceanographic fleet; 3) robustness to permit the system to be handled and launched even in rough seas; 4) rosette to collect "clean" water samples for chemical and biological analysis; 5) real time display of profile data for optimum selection of discrete water samples at depth; and 6) computer interface for rapid preliminary data reduction at sea for timely comparison with contemporaneous remotely sensed and other shipboard data sets. In short, BOPS is an interdisciplinary (optical, physical, chemical, biological) analogue to the conventional physical oceanographic Conductivity-Temperature-Depth (CTD) system.

2. BIO-OPTICAL PROFILING SYSTEM

The Bio-Optical Profiling System II (BOPS-II) is an integrated data collection and analysis system designed to provide rapid and accurate measurement of the variability of ocean optical and ancillary properties in the upper 500 meters of the ocean (Fig.1). It is a redesign of the original BOPS [1] which was made compatible with the first ocean color satellite (Coastal Zone Color Scanner, CZCS) for the Warm Core Rings Program[15]. Table 2 lists current instrument components of BOPS-II while Figure 2 is a block diagram showing the relationship of the underwater unit to the shipboard deck unit and the computer system. The physical layout of optical sensors includes downwelling irradiance sensors whose top profile is above the top of the water bottles and out and away from the cable termination (a potential source of shadowing). The physical sensors are in a plane at the bottom of the package to minimize interference with temperature and salinity sensors in order to optimize their data on the descending profile. The stand and the protective ring at the top of the package provide important protection from inadvertent bumping the side of the ship and for attaching handling lines during instrument deployment and retrieval during rough seas. For Antarctic work aboard the R/V Polar Duke, the BOPS-II has been deployed from the ships stern both because the A-frame provides the longest reach away from the ship and for protection and stability in stormy weather.

2.1. Optical components

While the BOPS-II has been periodically upgraded, within the constraints of resources and a demanding field deployment schedule, many components of this system are nearly a decade old. More recent systems are described in Sect. 2.3 below. A primary objective of this article is to describe a field-proven instrument, illustrate the robustness of a system that has been used for over 1600 casts mostly in the Southern Ocean under extreme environmental conditions, and to document the optical calibration history, and hence optical precision and accuracy, over time.

The central components of the underwater BOPS-II are two MER-2040 microprocessor controlled spectroradiometers. Each MER can digitize up to 64 analog and 3 frequency inputs, so many additional sensors can be added including scalar irradiance, transmissometers and fluorometers. The optical sensors of the MER-2040 are based on arrays of solid-state photodetectors. Each photodetector assembly is composed of a high shunt resistance, blue enhanced silicon photodetector hermetically packaged with its own custom narrow-band interference filter. Blocking filters are added to reduce stray light levels, typically to values below the sensitivity detection levels of the sensors. Each detector is connected to an electrometer amplifier with sensitivity optimized for wavelength and geometrical configuration. This array of detector assemblies with amplifiers is scanned under microprocessor control at a rate of approximately one channel per millisecond.

The current optical characteristics of the BOPS-II were selected to meet SeaWiFS requirements (Table 1) including accurate cosine response and quantitative measure of the immersion effect [16]. The irradiance detector arrays view the inside of a cosine corrected optical collector. To test the cosine response of the design, a MER-2040 was placed on an automated rotating arm in a water-tight test tank equipped with nonparallel sides. A collimated beam was positioned to fill the collector at the precise center of rotation of the assembly. Under computer control, the instrument is rotated in 5° increments from +90° to -90° "zenith" angles and the response from each channel recorded relative to the source. The cosine response of the instrument agrees with the cosine rule within ± 5% out to angles of 75° and ± 10% to 85°. Immersion coefficients used in the calibrations are those from tests conducted at Biospherical Instruments on MER Series spectroradiometers. The immersion coefficient of the collector was determined experimentally from irradiance measurements made in air and under water [16]. The instrument was carefully positioned in a test tank beneath a calibration lamp fixture. Readings from the lamp were recorded in air and at 5 cm depth increments both during filling and emptying the tank. Following SeaWiFS protocols[17], these data were used to measure the attenuation coefficient for the water used in the test and to solve for the immersion coefficient at each wavelength. BSI currently offers collectors with more accurate fidelity to a cosine response.

The radiance array consists of a cluster of "Gershun Tube" radiance collectors which view the upwelling radiance through an acrylic pressure window. The radiance collector array was designed with a half-angle field of view of 10.2° in water and 13.7° in air with later versions reduced to 10.0° field of view in water.

A maximum of eight MER-2040s can be networked into the same data stream and synchronously sampled on a single serial data port. In the case of the BOPS-II configuration, two profiling MER-2040 spectroradiometers interface with a MER-2020 with a MER-2040 EPROM serving as an above water sensor with 4 channels of downwelling irradiance (410, 441, 488, and 560nm). In addition, a sub-surface floater [18] containing a MER-2020 with a MER-2040 EPROM has been used to provide the downwelled spectral irradiance just below the surface, $E_d(0^-,\lambda)$, at 5 wavelengths, and the upwelled radiance about a meter below the surface, $L_u(1m)$, at 5 wavelengths including 683nm. This floater uses a 50m kevlar conducting tether and floats away from the ship to avoid ship shadow problems. This component of the BOPS-II will be particularly useful for satellite comparisons with SeaWiFS and other ocean color satellite sensors. As the floater requires extra time to deploy, it is deployed when sampling constraints allow sufficient time and remains deployed perhaps for an entire day.

The BOPS is extensible in that auxiliary instruments may be interfaced. For instance, a transmissometer, [19] accurately measuring beam transmission in a 25 centimeter water path, uses a modulated light emitting diode (660nm) and a synchronous detector. This instrument contains stable temperature compensated electronics and provides data with an error of less than 0.5% transmission. Also, a scalar irradiance quantum meter [20] is used to measure photosynthetically active radiation (PAR). Scalar irradiance PAR is the number of photosynthetically active photons arriving at a point from all directions within the wavelength band 400-700nm.

2.2 MER-2040 Hardware and Software

To accommodate the wide dynamic range encountered in the ocean, the signals are digitized by a data acquisition system composed of a 14 bit analog to digital converter (ADC) with a computer controlled input amplifier with selectable gain ranges of 1, 16 and 256, yielding a dynamic range of approximately four million to one. To compensate for the small temperature sensitivities inherent in silicon detectors and amplifiers, temperature sensors located in close proximity to the detectors and amplifiers and digitized.

A design feature of the MER-2040 has allowed us to modify the electronics module within the General Oceanics Rosette so as to allow better firing of the water bottles. A simple circuit is used which permits bottles to be tripped within 1 sec of a computer keystroke and which provides a signal change within the data stream confirming the tripping of each bottle. Eliminating the need to halt the winch at each sample depth has significantly simplified and speeded up our profiling. The UCSB software searches for the change in voltage level and prints out a confirmation line with depth in addition to other parameters for output onto water sample worksheets.

The microprocessor within each of the BOPS MER units is programmed for flexibility. The surface computer sends information to each unit specifying which channels to sample, the order of sampling, and the gain to use for each channel. The frequency counting channels are also programmed to select the number of cycles of each signal to count. Commands are sent to specify whether multiple scans of the programmed analog channels are to be averaged and the time interval between the start of each sampling. Another command allows multiple repeats of each sampling suite to proceed automatically. The result is that multiple instruments can be configured so that all sample synchronously and store their averaged data internally until the data are requested by computer command. If a different number of channels is requested in each instrument, the number of scans that are averaged can be specified so that each instrument takes the same time for completion. Thus not only would the sample start time be synchronized, but also the sampling time window. For example, the MER-2040 with irradiance sensors on both ends measures 36 channels 10 times during each programmed sampling window. The other unit, having scalar irradiance and radiance channels, measures 15 channels but does so 24 times. The modified MER-2020 surface unit (running at half the clock rate) measures 9 channels but averages 35 scans.

We have carried out tests to show that each instrument can complete all required sampling at our desired rate of three times per second. The frequency counting circuitry uses the sine-wave signal from the Sea-Bird temperature and conductivity probes to gate on, and then off, the counting of a 6 MHz reference frequency for a specified number of cycles. By measuring the cycle period (as distinct from the frequency), the necessary high resolution is retained even though the sampling window is less than 350 ms.

With each MER unit programmed to complete its analog and frequency sampling within a selected time and programmed to start each sampling at a given time spacing, the surface computer needs only to request a data scan from each unit as it becomes available. The sampling interval is also dependent on the speed of the surface computer which must retrieve each scan of data from all instruments, combine the strings and write to a data file, as well as display selected parameters in a real-time graphic display. With a data rate of 3 scans per second, we use a lowering speed of about 25 m/s through the euphotic zone (1% PAR depth) to assure sufficient data for accurate determination of the diffuse attenuation coefficients. Winch speed can then be increased to roughly 35 m/s for the remainder of the cast. Although most casts have little detectable irradiance below 200 m, we continue to 500 m, or 10 m above the bottom, in order to obtain a fuller hydrographic data set with the CTD and other sensors on the BOPS-II. On a profile to 200 m, 1600 data frames are typically recorded on both the down- and up-casts.

The BOPS-II is operated over a three conductor armored cable with power and data on separate conductors. Before transmission, each data frame is encoded with a start byte, instrument status and identification byte, and a checksum for verification of proper transmission. The readings of each optical sensor are then transmitted up the cable to the deck unit via asynchronous serial communications using an RS-232 interface. The system is limited to cable lengths less than 1000 meters on a standard CTD cable.

The current shipboard components of the system include a constant current power supply for the underwater system, a 486 microprocessor with 6 MB RAM, a 2 GB disk drive, a high resolution graphics display system, printer and tape backup system. The system also makes use of a third MER-2040 mounted shipboard for reference recording of incident irradiance above the surface to correct for changing atmospheric conditions during a vertical profile.

2.3 MER-2040 Series Instrument Evolution

The MER-2040 has evolved significantly since it was originally deployed on the BOPS-II. The optics have been expanded and the MER is available with up to 13 channels of downwelling irradiance, $E_d(\lambda)$, and 13 channels of either upwelling radiance, $L_u(\lambda)$, or upwelling irradiance, $E_u(\lambda)$. A special version of the MER called the MER-2048 is available featuring 13 channels of downwelling irradiance and seven channels each of both upwelling radiance and irradiance. Optimized for use into the ultraviolet region of the spectrum, the cosine collector on this 2040 series instrument has been redesigned to use a quartz-backed, vacuum-formed Teflon® diffuser. A modified version of the collector optimized for use in air is used on the MER-2041 Surface Reference Radiometer. Although the exterior dimensions have not changed, internally the newest MER features a low noise, 16 bit, bipolar analog-to-digital converter for data acquisition as well as eight digital I/O ports. Communications can be performed over a four conductor, 1000 m serial cable or using FSK over up to 10 km armored (single or multiple conductor) coax cable. In addition to those listed for the BOPS, the Remote Data Spooler (RDS) option for the MER-2040 affords operation with up to four additional serial-output instruments such as the WETLabs' AC-9, and the newest generation of intelligent rosette, such as those manufactured by General Oceanic or Sea-Bird Electronics.

2.4. Biological components

Chlorophyll and related pigments are the dominant absorbing constituents in the upper layers of productive ocean waters, and are therefore a key link in the bio-optical description of these waters [21,22]. In addition, chlorophyll is used as a measure of phytoplankton biomass and is the pigment that has the primary influence on ocean color and hence CZCS imagery [23-26]. BOPS-II uses a fluorometer for the continuous measure of chlorophyll and a rosette sampler to obtain discrete water samples from depth. The discrete water samples are used to obtain an extracted chlorophyll concentration, which is used to calibrate the fluorometer profile [27] as well as provide samples for analysis such as nutrients, primary production, dissolved gases, and microbiological parameters.

A fluorometer excites chlorophyll fluorescence in the blue and senses the output in the red region of the spectrum, providing a continuous measure of chlorophyll fluorescence as BOPS-II is lowered through the water column. After viewing vertical structure of chlorophyll fluorescence, beam transmittance, temperature and a selected irradiance channel in real time on the "down cast", the 12 bottle rosette is used to sample at representative depths on the "up cast" both for calibration of the fluorometer and to sample specific features and/or optical depths for use by other disciplines. A molecular oxygen probe [28] provides a profile of the dissolved oxygen.

2.5. Physical components

The BOPS-II contains temperature, conductivity and depth sensors in order to provide an accurate physical description of the water column. The Sea Bird temperature probe sensing element is a glass coated thermistor bead with an absolute accuracy of ±0.01°C and a useable resolution of better than 0.0001. The conductivity sensing element[29] is a two-terminal platinum electrode flow through cell with an absolute accuracy of 0.001 Siemens/meter and a usable resolution of better than 0.0001. The frequency output from these sensors is measured using the period averaging inputs of the MER-2040. Period averaging preserves the inherent accuracy of the sensors while permitting sampling rates of several per second.

Each of the MER-2040s compromising BOPS-II is equipped with a pressure transducer. One uses a quartz frequency output transducer (Paroscientific) with a 6.21MPa full scale with a typical accuracy of 0.01%. The output from this is digitized using the MER period averaging interface. The second unit is equipped with a strain gauge transducer with a similar full scale. Angle sensors on 2 axes are included to measure the package orientation during profiles.

2.6. Data Processing, Instrument Calibration and Error Analysis

BOPS data processing, calibration and binning have been discussed elsewhere [30-33]. Specific consideration has been given over the years to particular topics to be considered for the processing of in-water spectral irradiance data such as the influence of: the air-water interface[34], ship shadow effects[18,35,36] and surface albedo[37-39]. For BOPS-II, calibrations have been supplied by Biospherical Instruments Inc. upon delivery of the MERs while subsequent calibrations have been performed at the UCSB Ocean Optics Calibration Facility.

Each of the sensors on the BOPS (Table 2) has its own calibration procedure which is used to achieve and maintain the performance specifications as listed in Table 3. For example, the spectral irradiance arrays are calibrated using an FEL 1000 watt standard of spectral irradiance [40]. The radiance calibrations have used both a 20 inch integrating sphere and, more recently, 24 inch Spectralon® diffuse reflectance plaque. Our normal procedure, when logistics permit, is to calibrate both before and after each cruise. An eight year calibration history of the spectral downwelling irradiance channels on the BOPS-II is shown in Figures 3. These figures illustrate several points regarding calibration maintenance of an optical field instrument over time. (1) Wavelength channels which 'degrade' become obvious outliers (Fig. 3a), can be 'flagged' as problem channels and subsequently replaced (e.g. channels 410 nm and 520 nm were replaced prior to our 1992 field work). Identifying and replacing degrading components is a critical reason to maintain a protocol of periodic calibration. (2) Even though subjected to periodic transportation (by air and ship) between Santa Barbara and Palmer Station, Antarctica and to intense usage in often extreme environmental conditions, the mean drift of the calibration (stable channels) over time is negligible and the scatter is less than a few percent (Fig. 3b). (3) A calibration in the field was made in 1993 by transporting calibrated lamps and an optical bench to Palmer Station. The result of this effort was inconclusive because of the potential that the calibration lamps themselves may be more susceptible to change with shipment across the ocean than the optical components to be calibrated. Also, quality space for optical calibration with appropriate light baffles, etc. is difficult to achieve in the field. (4) In early 1995 the sensor head was rebuilt, and some channels added or replaced. (5) The 'optical train' including cosine collector, filters, photodiode, amplifier and analog to digital conversion circuitry is a robust system that, with periodic calibration, can maintain stability within a percent or so over relatively long times and harsh working conditions. Finally, and this is a key point, repeated, periodic recalibration is an essential element of meeting the optical protocols for time-series observations and to support the calibration/validation of the next generation of ocean color satellite sensors.

The cosine response and immersion coefficients, which allow transfer of an air calibration to an underwater calibration, were determined as described above (Sect. 2.2). We tested and found that there was no observed depth dependence, caused by temperature changes, for the irradiance sensors. Bandwidth and wavelength accuracy of the MER Spectroradiometer were determined by comparison with a double grating monochromator and are listed in Table 2.

The transmissometer calibration is checked by first carefully cleaning the windows, and then comparing the output voltage in air with the "air calibration" provided by the manufacturer. This instrument calibration also can be checked occasionally, since the optical properties of ocean waters can be constant over large areas when below the euphotic zone. In the North Pacific, during a 6 week period with more than 40 casts into the same 200 meter water, the beam transmittance repeated to within ±0.02%.

Fluorescence, as measured on the BOPS instrument, is a relative indicator of chlorophyll concentration. The rosette sampler is then used to obtain water samples from depths of interest, and the chlorophyll concentration of these discrete samples is determined fluorometrically in a laboratory calibrated fluorometer [27]. These discrete values of chlorophyll, which can be determined to ± 15%, are then used to calibrate the continuous fluorescence trace.

3. DISCUSSION

An exciting aspect of oceanography is the capability to view, via satellites, large areas of the oceans synoptically. The perspective provided by aircraft and satellite data is giving insight into a wide range of research areas [41] including the study of physical and biological processes on space and time scales previously unattainable. The next generation of ocean color satellite sensors [10] will carry this effort through the next decade. The new satellite technology has required a new approach to obtaining shipboard biological and optical data in order to provide both "synoptic" shipboard data as well as contemporaneous surface information for calibration/validation of aircraft and satellites. The versatility and flexibility of the BOPS-like instrument has provided one successful approach as evidenced by its use in a variety of programs including Warm Core Rings[42-45], the Optical Dynamics Experiment (ODEX)[46], Watercolors[47-51] Biowatt[22,52-57], Icecolors90[58-60], the Long-Term Ecological Research Program (Palmer LTER) [9,61-63], the Bermuda Atlantic Time Series (JGOFS/BATS) [36,64] and the Tropical Ocean-Global Atmosphere/Coupled Ocean Atmosphere Response Experiment (TOGA/COARE)[65]. Careful and periodic optical calibration is an essential element of an ocean optics field program. The Bio-Optical Profiling System II, including it's calibration history, is a robust interdisciplinary oceanographic instrument capable of providing accurate and precise optical data over long time periods.

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Figure 1. Photograph of the Bio-Optical Profiling System underwater unit.

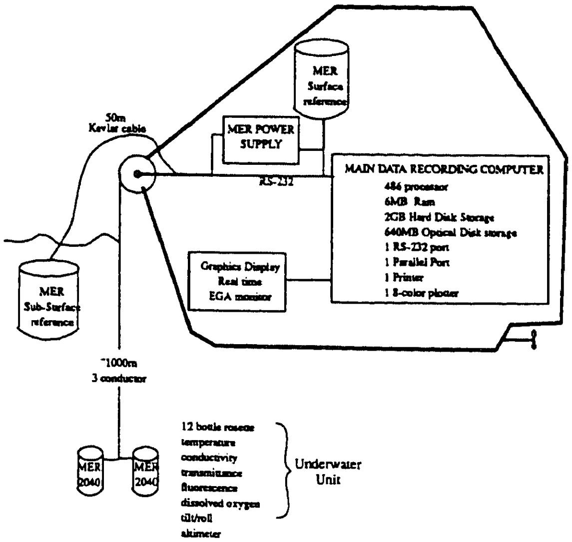

Figure 2. Schematic diagram of the BOPS integrated system showing the principal components of the underwater and the deck units connected by means of a hydrowinch and slip-rings.

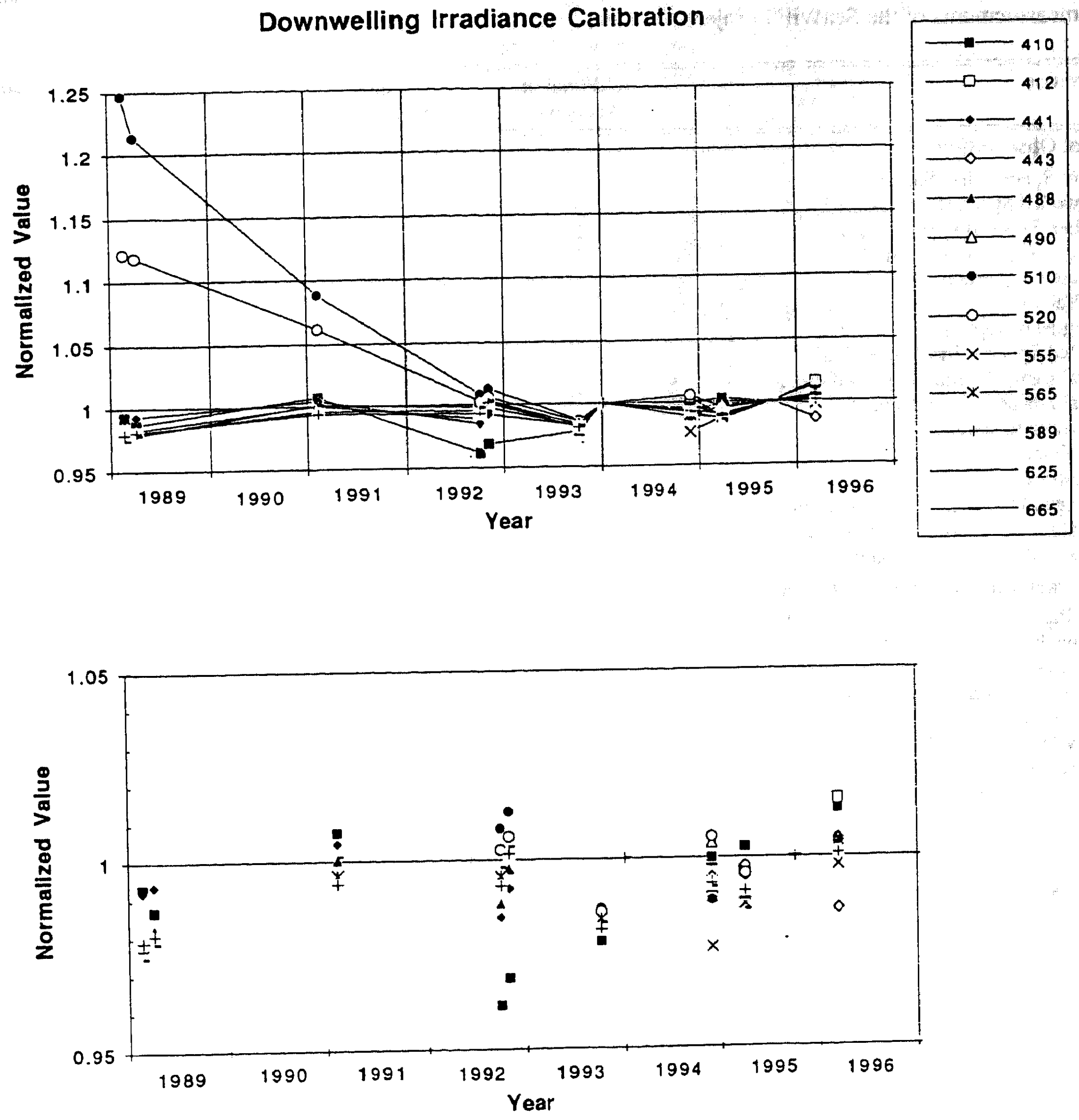

Figure 3. The eight year calibration history of the downwelling unit (MER8714) of the Bio-Optical Profiling System II in normalized units versus time. The top panel shows data on channels which prematurely degraded and were replaced. The lower panel displays an expanded scale for the remaining channels.

Table 1. Observation requirements for Calibration/Validation, Algorithm Development, and Supporting Science for SeaWiFS. The observations indicated under Calibration/Validation and Algorithm Development are considered Core measurements of the SeaWiFS Project.

Observation	Calibration Validation	Algorithm Development	Supporting Science	BOPS-II
Optical Observations				
Incident Spectral Irradiance-Ed,(0,-)	X	X		+
Downwelled Spectral Irradiance-Ed,Z	X	X		+
Upwelled Spectral Radiance-Lu,Z	X	X		+
Spectral Solar Atmos. Trans (Ta)	X	X		-
Sea State photograph	X	X		-
Wind Velocity	X	X		-
Drifting Buoy Optics			X	-
Upwelled Spectral Irradiance-Eu,Z			X	+
Spectral Beam Attenuation Coefficients			X	x
Spectral Absorption coefficient			X	a
Red beam attenuation			X	+
In situ Fluorescence Profile			X	+
Sky Radiance			X	-
Submerged Up Radiance Distribution			X	-
Spectral Backscattering coefficient b_b			X	x
Spectral Volume Scat. Function			X	x
Biological/Chemical/Physical Observations				
Phyto. Pig (Fluor. Tech.) Chlor. and Phaeo.		X		w
Phytoplankton Pigments (HPLC ^{1})		X		w
Total Suspended Matter (TSM) Conc.		X		w
Dissolved Colored Organic Material		X		w
Aerosol samples			X	-
Primary Productivity (^{14}C , O_2)			X	w
Temperature and Salinity Profiles			X	+
Phycobilipigments (mg/m^3)			X	w
Particle absorption coefficient			X	w
Detritus absorption coefficient			X	w
Phytoplankton absorption coefficient			X	w
Organic Suspended Matter Conc.			X	w
Inorganic Suspended Matter Conc.			X	w
New Production (^{15}N)			X	w
Coccolith Concentration			X	w
Humic and Fluvic Acids			X	w
Microphotometric particle absorption			X	w
Particle fluorescence spectra			X	w
Sinking Flux/Sed. Traps			X	-
Particle size spectra			X	w
Total Dissolved Organic Carbon			X	w
Airborne Fluorescences			X	-
Airborne Radiances			X	-
Phytoplankton species counts			X	w
Grazing Losses			X	w

[1] High Performance Liquid Chromatography

x = can be added
+ = now
a = from g... relate..; not accurate
w = potential-using discrete water sample
- = not applicable

Table 2. Instrument components of BOPS underwater unit.

Instrument	Manufacturer	Property Measured
spectroradiometer (MER-2040)	Biospherical Instruments, Inc.	downwelling irradiance upwelling irradiance upwelling radiance chlorophyll fluorescence band scalar irradiance spectral PAR
transmissometer	SeaTech, Inc.	beam transmittance at 660nm
fluorometer	SeaTech, Inc.	chlorophyll fluorescence
ocean thermometer (SBE 3)	Sea-Bird Electronics, Inc.	temperature
conductivity meter (SBE 4)	Sea-Bird Electronics, Inc.	conductivity (salinity)
oxygen probe (SBE 13-01)	Sea-Bird Electronics, Inc.	dissolved oxygen
pressure gauges		depth
quartz	ParoScientific	
strain	SensoTec	
rosette (twelve 5 or 12 liter)	General Oceanics	discrete water samples
AccuStar electronic	Schaevitz	tilt and roll
altimeter	DataSonics	distance from the bottom

Table 3. Performance Specifications for the Bio-Optical Profiling System (BOPS)

Spectroradiometer (Spectral Irradiance):
Downwelling Irradiance: 410,412,441,443,488,490,510, 520,555,565,589,625,665nm
Upwelling Irradiance: 410,441,488 520 565 589,625nm
Upwelling Radiance: 410,441,488,520,565,625,chl fluorescence
Bandwidth: 50% points +5nm, -5nm; 1% points +15nm, -20nm
Wavelength Accuracy: ±2nm
Radiometric Accuracy: 5%
Stray light: <0.01% 40nm from peak; <0.0001% 100nm from peak

Scalar Irradiance:
Downwelling Scalar Irradinace: 410, 441, 488, 520, 565nm
Equal Quantum Response (PAR): 400-700nm

Data Acquisition Systems:
Analog Channels per MER-2040: 56
A/D Conversion: float (12 bit mantisa, 4 bit exponent); integer (16 bit)
Frequency Channels per MER-2040: 3
Frequency Conversion: integer (24 bit)

Data Transmission:
RS-232: 9600 baud (up to 38,400 baud)
Maximum Cable Length: 1000 meters 3 conductor armored cable
Acquisition, Process, Transmit Time: 2.5 msec/channel at 9600baud

Depth Sensor (ParoScientific):
Range: 0-600m
Pressure Accuracy: ±0.04% at 250m
Depth resolution: 0.1m
Other: includes internal temperature sensor

Temperature Sensor:
Accuracy: ±0.01°C
Long term stability: ±0.003°C per 6 month
Resolution: .0001°C

Conductivity Sensor:
Accuracy: 0.001 Siemens/m
Long term stability: 0.0003 Siemens/m per month
Resolution: .000001 S/M

Tilt/Roll:
Range: ±45°
Accuracy: ±1°

Transmissometer:
Wavelength: 660nm
Pathlength: 25cm
Accuracy: ±0.5%

Oxygen Sensor:
Range: 0 - 15ml/l
Resolution: 0.01 ml/l
Time Response: 10 seconds

Data Recording & Control Computer:
Processor: 486
Storage: 2GB disks; 650 MB optical disk
Memory: 6MB RAM