MODIS Team Member - Semi-annual Report

Marine Optical Characterizations
June 2001

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NOAA/NESDIS

SUMMARY

Since the launch of NASA's TERRA satellite, the Marine Optical Characterization Experiment (MOCE) Team has continued to acquire and provide at-sea observations for MODIS initialization and calibration tasks. The Marine Optical Buoy (MOBY) system has been acquiring optical and basic meteorological observations coincident with TERRA's overpasses in support of the Moderate Resolution Imaging Spectrometer's (MODIS) ocean color mission.. During this period, the team conducted eight field campaigns in Hawaii in support of the MOBY project. These cruises, designated MOBY-L63 through MOBY-L69, serviced the MOBY215, MOBY216 and MOBY217 systems. Marine Optical Characterization Experiment (MOCE-8) was carried out in Hawaii in February - March 2001 in conjunction with the MOBY swap out to provide additional initialization data for the MODIS side b electronics configuration. A match up MOBY and MOCE database was produced for the side b coincident overpasses for the 31 October 2000 through 11 March 2001 time period. This data base is being utilized as the initialization data set for the iterative process of testing and evaluating the MODIS ocean spectral band vicarious calibration in both the Goddard and University of Miami code versions. The results of these comparisons are forwarded to Miami for their evaluations.

During this period the bio-optical products were reformulated utilizing an improved Nimbus -7 CZCS and MOCE data set. The new algorithm forms along with new quality control criteria were forwarded to Miami for coding in March 2001. These products are presently being evaluated as the nLw product evolves. Additionally, the team is continuing to provide the SeaWiFS Project observations for their validation and long term calibration tasks and collaborating with NIST personnel in conducting stray-light characterizations of the Moby/MOCE optical systems. A summary of the team activities during this reporting period are shown in Figure 1.

FIELD OPERATIONS

MOCE-8

MOCE-8 occurred February 28 - March 9, 2001 aboard the R/V Ka'imikai-o-Kanaloa. The science party personnel and affiliations for MOCE-8 are listed below.

NOAA - Dennis Clark, Edwin Fisher, Eric Stengel, Marilyn Yuen, Yong Sung Kim, Larisa

Koval, Mike Ondrusek

MLML - Mark Yarbrough, Mike Feinholz, Darryl Peters, Rachel Kay, Stephanie Flora, John Heine, Terry Houlihan, Nisse Goldberg, William Broenkow

CHORS - Chuck Trees, Chris Kinkade, Jim Mueller

University of Miami - Hong Du, Ken Voss, Albert Chaplin
NASA/GSFC - Robert Barnes, Gerhard Meister

NIST - Steve Brown, Carol Johnson

Mooring Systems Inc (MSI) - Peter Clay, Doug Dooner

Hawaiian Rafting Adv - Steve Juarez, Earl Keatly, Fran Keatly, Rob Wheeler

The cruise objectives were to terminate the MOBY-215 deployment, begin the MOBY-216 deployment, and provide radiometric characterizations and spatial variability of water-leaving radiances and atmospheric transmittances concurrent with MODIS and/or SeaWiFS observations. MOBY215 and the deep-sea mooring were recovered on the 28th during the first leg of the cruise. Before returning to Snug Harbor on March 1st, the new mooring was deployed with the assistance of Mooring System, Inc (MSI) personnel. The new mooring's witness buoy incorporates the updated MOBY Meteorological and Oceanographic Buoy (MMOB2), which is configured as a semi-taut mooring deployed in approximately 1200 m of water. The surface float is a 3-m diameter Guardian style buoy with running lights, radar reflector and solar panels (Fig. 2). The mooring line consists of 3/4"chain, 5/16" plastic jacketed torque balanced wire rope, 3/4" nylon line short spliced to 3/4" polypropylene, 20 - 17" glass flotation spheres on 1/2" chain and a single EG&G acoustic release. The remainder of the array is 1/2" chain, 1"nylon line and a 3000 lb anchor. The meteorological suite of instruments includes redundant R.M. Young anemometers, Costal Environmental air temperature thermistors, Vaisala relative humidity sensors and a single Honeywell barometric pressure transducer. A WetLabs Wetstar fluorometer and a SeaBird 371M Microcat are mounted approximately 1.5 m below the surface (Fig. 3). The data are logged on a Costal Environmental Systems ZENO-32 data acquisition system and also downloaded to the shore based MOBY lab at Snug Harbor Hawaii daily via a cell phone modem.`

MOBY216 was deployed during the second leg of the cruise on 4 March. Two sets of initial diver-reference measurements were made on the 8th with the assistance of HRA personnel.

A complete suite of measurements, designed to characterize the bio-optical state, were performed at nine stations during satellite overpasses. Clouds and high winds were detracting factors during data collection for seven of the nine stations. SeaBird CTD, SPMR, MOS and FOS casts were conducted at most stations. CTD casts and alongtrack water collection resulted in 73 TSM/POC/PON samples, including sample replicates at each satellite overpass. During the cruise, 39 pigment samples were collected during CTD casts, 35 samples were collected during MODIS and SeaWiFS overpasses, 108 samples were collected during alongtrack sampling, and 6 during MOS/FOS profiling. Replicate pigment samples (188 * 2) were collected so that they could be processed on board the ship using the fluorometric method. Pigment samples were also frozen in liquid nitrogen for HPLC analysis back at CHORS.

During the cruise, a Spectrex Laser particle counter was used to characterize the amount and size of particulates during tracklines, overpasses and profiling during CTD stations. Using data collected by the particle counter, we can match up high counts with increases in bean attenuation and with increases in the chlorophyll *a* concentrations.

Hand Held Contrast Reduction Meter (HHCRM) measurements, to derive spectral transmittances, specifically bracketed each overpass. Water vapor column, ozone column, and aerosol optical depth were measured using MICROTOPS II during each overpass.

The observations acquired provided a variety of marine optical, atmospheric, and biological signals for algorithm development, calibration and validation purposes. Detailed description of the cruise activities, including the MOCE-7 characterization cruise, are contained in Appendix 1.

Drs. B. Carol Johnson and Steve Brown from NIST worked in Hawaii in March during the fifth NIST/MOBY inter-comparison effort. Additionally, Gerhard Meister from the NASA SIMBIOS project participated to develop protocols for his future work. Spectral Radiance from MLML sources (OL420 and OL425 spheres) and a NIST source (NPR sphere) was repeatedly measured under several configurations via the NOAA/MLML SLM-L’s, the EOS VXR, and the SIMBIOS SXRII. Additionally, several NIST monochromatic laser sources were employed during further investigations into the MOS spectrometer’s stray-light characterization. The profiling MOS, MOS202cfg08, Ed and Lu ports viewed NIST HeNe, Ar, and tunable diode laser output, and MOBY215 LuMid and LuMOS collectors measured Ar laser lines. These measurements examined the feasibility of using a new NIST laser facility to address the MOS stray light problem.

Robert Barnes from NASA GSFC/SAIC was also on-site at MOBY Hawaii Operations to work on a paper describing MOBY calibration procedures. MLML and NIST personnel also worked with him on preliminary data modeling the MOS stray light characterization/correction scheme.

MOBY-L69 (M219SOB)

The MOBY-L69 recovery and replacement cruise occurred June 1 - 4, 2001 aboard the R/V Ka’imikai-o-Kanaloa. The following personnel participated:

NOAA - Dennis Clark, Ed Fisher, Yong Sung Kim, Mike Ondrusek, Eric Stengel

MLML - Mike Feinholz, Mark Yarbrough, Darryl Peters, John Heine

University of Miami - Ken Voss

HRA - Steve Juarez

MOBY217 was deployed without incident on the 1st of June, but the weather changed late that afternoon, so the MOBY216 was placed under tow for the night. On June 2nd, MOBY 216 was successfully recovered, MLML and NOAA divers deployed the WARS camera and rocker-stoppers, and the battery rack and controller box from the MET station were removed. Station #1 operations commenced on June 3rd at the Lanai MOBY Mooring site - RADS, MOS, FOS, and Satlantic optical profiling ensued while divers acquired initial diver calibrations on MOBY217. The same day the repaired MET station's battery system was replaced; however, the controller was non-operational and was removed for repair work. Station #2 on June 4th saw shipboard optical profiles, WARS camera retrieval, and the repair of the witness buoy marker light.

The new Satlantic Inc. radiometers were delivered to the MOBY site before the cruise. Both the MICROPRO and MICROREF instruments have 14 channels allowing for greater spectral resolution within the visible region. Programs have been written to convert binary counts to radiometric units, similar to those for the SPMR and SMSR. During the cruise, test casts were conducted to compare the measurements taken by both profilers.

INSTRUMENT CALIBRATIONS

MOBY

During this reporting period, MOCE team members and professional divers conducted six calibration excursions via Hawaiian Rafting Adventures (HRA) chartered dive boat to perform the diver calibrations (MOBY-L63 - MOBY-L68). During MOBY-L63 (January 8 - 11), Meteorological station (MET) and CIMEL maintenance was performed and MET data were downloaded. It was noted that the buoy's top arm was bent downward - presumably MOBY had become entangled with the mooring's witness buoy. MOBY optical collectors were cleaned and "after-cleaning" diver-reference-lamp scans were performed. During MOBY-L64 (January 24), the tether was unwrapped from MOBY215, underwater photos were taken of the buoy, and the status of the bent top arm was assessed (Fig. 4). During the MOBY-L65 service cruise (February 6 - 8), MET and MOBY calibration data were downloaded, MOBY sensors were cleaned and diver calibrations were performed. Water samples were collected and filtered for CHORS pigment analysis. The WARS controller and underwater camera were recovered from MOBY 215 and returned to Snug Harbor during MOBY-L66 (March 18). During MOBY-L67 (March 6 - 9), MOBY216 before-cleaning diver reference lamp scans were performed, optical collectors were cleaned, and the Lanai CIMEL instrument was serviced. During MOBY-L68 (May 21- 23), the ARGOS battery on MOBY216 was replaced, and the routine maintenance at the CIMEL site was performed.

RADIOMETRIC STANDARDS & RADIOMETERS

Team personnel stationed at the NOAA operations facility at Snug Harbor, Hawaii continued maintenance of our NIST-traceable radiometric standards and performed calibrations of our radiometers. We purchased a new one-piece aluminum baffle for the Gamma Scientific GS5000 system's housing to replace our aging honeycomb-style baffles which are no longer supported by

Gamma. Initial experiments indicate, however, that the new baffle may alter the spectral output of the system - further investigations are pending while we continue to use the old baffles for MOBY, MOS, SIS, and FOS calibrations. Two irradiance standards, FEL-F454 and F471, were hand-carried from Hawaii to Maryland in December 2000, were re-calibrated by NIST in February 2001, and returned to Hawaii before the MOCE-8 cruise. We took delivery in April of hardware and software to upgrade our precision current supply system for 1000 Watt Irradiance FEL standards. We purchased two Agilent 3497A Data Acquisition/Switch Units with reed-relay multiplexers, two HP/Agilent 6030A DC Power Supplies, one L & N 4361 Precision Shunt from Process Instruments Inc., and a PCMCIA-GPIB card and LabVIEW software upgrade from National Instruments. This new system will be in accord with most-recent NIST practices.

Radiometric calibrations during the reporting period included:

1. Post-deployment calibration of MOBY214 and MOS204cfg04 in January 2001
2. Pre-deployment MOBY215 and MOS205cfg05 in November 2000
3. Post-deployment MOBY215 and MOS205cfg05 in March/April 2001
4. Pre-deployment MOBY216 and MOS204cfg05 in February 2001
5. Post-MOCE7 MOS 202cfg08 and SIS 101cfg04 in January 2001
6. Pre-MOCE8 FOS in January 2001
7. Pre-MOCE8 MD512 VIS and NIR in February 2001
8. Post-MOCE8 FOS in March 2001
9. NIST-2001 #1 MOS202cfg08 Ed & Lu via NIST HeNe and Argon lasers in March 2001
10. Post-MOCE8 SIS101cfg04, MOS202cfg08, MOS205cfg05, MOBY215 in May 2001
11. NIST-2001 #2 MOS202cfg08 Lu & Ed at NIST via OL420 and SIRCUS in April and May
12. Pre-L69 MOS205cfg06 and MOBY217 in May 2001

Detailed listing of calibrations and maintenance for each standard and instrument are provided in Appendix 2.

In April 2001, Mark Yarbrough and Mike Feinholz traveled to Gaithersburg, MD to work with Drs. Steve Brown, Keith Lykke, and Carol Johnson at NIST. A characterization of stray light in the MOS202 radiometer was accomplished and a preliminary correction procedure developed for up-welling radiance spectra. The correction algorithm addresses the discrepancy in the MOS spectrograph’s overlap region. Stray light is generated by forward-scattered (haze) and isotropic (diffuse) radiation from the single holographic grating plus any light scattered from other optical elements - this leads to MOS "out-of-band” signal. The NIST Spectral Irradiance and Radiance Calibration facility using Uniform Sources, SIRCUS, producing spatially uniform, monochromatic, broadly tunable radiance was used to accurately determine "in-band” and "out-of-band” components in measured MOS signal. The wavelength range 362 to 936 nm was measured at 2 to 5 nm intervals to characterize the entire spectral range of MOS responsivity. High resolution scans at 0.2 nm intervals were measured over several ranges: 430 - 440, 555 - 565, 760 - 770, 860 - 865 nm. High-resolution scans define the MOS blue and red spectrographs’ in-band profile, to be used in the Stray Light Correction Algorithm. Additionally, MOS viewed the NIST OL420 sphere with and without colored glass gilters to establish test conditions for correcting broadband blue-rich and green-rich spectra via a calibration response established with a red-rich source. Finally, a TT7 temperature characterization was attempted at blue and red wavelengths in and out of the overlap region. Over eleven hundred MOS scan sets were acquired during three weeks of measurements at NIST (see Appendix 2 for MOS202 calibration file listing).

A preliminary MOS Stray Light Correction Algorithm was developed to separate in-band and out-of-band components from MOS measured signal at each CCD pixel. This correction is applied to both responsivity measurements of a calibrated radiance source and in-water upwelled radiance measurements. High-resolution SIRCUS laser scans were inverted and fit to a Lorenzian function to produce the SSF, or slit scattering function, for both blue and red spectrographs. Second order reflections observed in the MOS spectrographs were also modeled and included in the SSF. Removing the in-band portion yields an out-of band SSF. The out-of-band SSF is convolved with uncorrected response or signal, and the integral estimates the stray light component at each pixel. Subtracting the stray light gives "corrected” values. Corrected values are then used as input and the procedure is iterated until a steady state solution is reached. The validity of the algorithm was checked by applying uncorrected and corrected responsivity to measurements of the NIST OL420 with blue and green filters and comparing to NIST-determined sphere output spectra. Preliminary corrections indicate MOS Lu’s are increased 3% and 6% at 412 nm. A NIST/NOAA/MLML poster outlining this work was presented at the 2001 Ocean Color Research Team Meeting in San Diego, California in May 2001 and contained in Appendix 3. NIST researchers are scheduled to return to Hawaii in July to execute further characterizations on MOBY216, and NOAA/MLML is investigating the use of a tunable laser system in Hawaii with varying MOS/MOBY configurations.

FOS

The calibration data from different cruises were compared to characterize the FOS performance and stability. The percent difference of post-MOCE-7 and pre-MOCE-8 calibrations shows that the irradiance part deviated about +/- 2% and radiance part of response stayed less then 1% (Figure 5). During the MOCE-8 cruise one of the FOS’s fibers was broken. The old fibers were replaced with the new fibers and they showed 30 % more responce (Figure 6)

WARS

Much progress has been made with the Wide Angle Radiance System during the reporting period. After calibrating the system in the fall of 2000, we were able to make quantitative measurements in conjunction with the University of Miami’s RADS (Radiance Angular Distribution System) during the December cruise and during the March cruise. An example of radiance data collected by WARS while attached to the top arm of MOBY on March 7, 2001 at noon is shown in Figure 7.

Utilizing data from these two systems during these two cruises, we were able to provide a relative correction to MOBY and MOS measurements which were due to variations in the angular distribution of upwelled irradiance. The corrections were spectrally dependent and were as high as 10%. These correction factors were then applied to MOBY and MOS measured upwelled radiance data at nadir when calibrating MODIS data measured at various zenith and azimuth angles relative to the sun. We were also able to confirm by constraining these correction factors that this bi-directional reflectance effect cannot account for the response versus scan angle problems.

CIMEL SERVICE

The Lanai CIMEL site was returned to fully-operational status in January 2001. This requires twice-monthly maintenance visits and any necessary installation, repair and/or upgrade support. In addition to the Lanai CIMEL site, our personnel in Hawaii also maintain a second site at Coconut Island off the East coast of Oahu, Hawaii. MLML has contracted a University of Hawaii graduate student, Stephanie Christensen to assist with routine maintenance. The Coconut Island site has been operational since June 2000, and is overseen by Chuck McLain at NASA GSFC for the AERONET (Aerosol Robotic NETwork) program.

DATA PROCESSING

MATCH UP DATABASE

Much time was spent collecting and processing daily MODIS normalized water leaving radiance (nlw) data over the MOBY site and comparing these data with data collected by MOBY. Since August 2000, we have had a data subscription set up with the MODIS Adaptive Processing System (MODAPS) at GSFC. Daily MODIS granules over the MOBY site near Hawaii were pushed by FTP to our local computer for comparison to MOBY data. Each day we received level 1 MODO3 files containing geolocation data, a level 2 MODOCL2 file containing normalized water leaving radiance data and a level 2 MODOCL2A file containing MODIS chlorophyll products. All three file types utilize an HDF format and have a one-kilometer resolution.

MODIS overpass data over the MOBY site is available every 14 out of 16 days at 14 different satellite zenith angles, then the pattern repeats. For the two missing days, the MOBY site is between orbits. For each day in which data are available, we utilize the exact GPS location for the MOBY buoy for that day and match up the nearest pixel on the HDF file corresponding to that day. Data are extracted in a 3 km by 3 km grid around that nearest point. For each pixel the data extracted are geolocation, nlw's (412 - 678 nm), data quality rating, mirror side, detector number, satellite and solar zenith and azimuth angles, atmospheric tau and epsilon, aerosol model used, and modeled pigment products. Average of the highest quality nlw for each wavelength is compared to MOBY nlw's corresponding to the overpass time (Table 1).

The data extraction for the MOCE match-up is the same as for MOBY except that the location for extraction is the ship's GPS location at the same time of the MODIS overpass and the nlw's are compared to MOS data collected from the ship (Table 1). During the end of 2000 and Spring 2001, we participated in two MOCE cruises off the coast of Hawaii. For the days we were on MOCE cruises, we also produced match-up data from granules processed by Bob Evans' remote sensing group at the University of Miami who are responsible for providing algorithm and code updates for the MODIS data processing at GSFC. The data received from the University of Miami corresponding to our MOCE cruises were processed using various updates of algorithms and code for comparison with our in-situ data

The processing of the MODIS data by MODAPS is approximately 60 days behind the data collection. We have been continuously producing data match-ups throughout the year 2000 and up to the present, as the data become available. On October 30, 2000, NASA switched MODIS internal electronics from Side A electronics to Side B electronics requiring separate validation and calibration processing. By January 2001, we were just starting to analyze the side B data. In January 2001, we participated in a MODIS Ocean Science Meeting in Columbia, MD. All the match-up and image data, analyzed by the MODIS Ocean Science Team personnel involved in algorithm and code development, consisted of Side A electronic data and products were considered Beta products. Beta products are derived using at-launch preliminary algorithms for evaluation purposes only. Some of the problems with the Side A beta products (Figure 8), identified at the January meeting, (many as a direct result of our match-up data set) are listed below.

- Calibration: The calibration utilized up to this time, from our MOCE6 April 2000 cruise, did not work consistently for the Side A beta products produced up to October 30, 2000. This was attributed to the other problems listed below and it was determined that calibration updates could be easily revised as data become available.
- Response versus Scan Angle: An east to west difference was noticeable across scan lines. It was determined that more work was needed to understand this problem.
- Mirror Side Differences: These differences contribute to the striping seen in Figure 8 and resulted in unbalanced gain settings between the mirror sides.
- Angle of Incidence: Detector responses changed as a function of Angle of Incidence contributing to the stripes in Figure 8.
- Digitizer noise in IR Bands: Determined that this was reduced when MODIS was switched to Side B electronics.
- Inter-detector difference: Gain settings between the ten detectors needed to be balanced and also contributed to the stripes in Figure 8.
- Polarization and Sun Glint Corrections: Settings were only approximate and needed to be revised.

All of these problems propagated into higher level products and it was determined that algorithm and code improvements were required and that continued calibration cruises and MOBY match-ups are necessary. It was also requested that all principal investigators supply revisions, if any, on individual product algorithms. The next meeting was scheduled for April 2000 in Miami, FL. Dennis Clark supplied revised MODIS pigment product algorithms to Miami in early March. Miami implemented the algorithms and new calibrations on a revised test, Side A, data set for the April meeting. We attended this meeting where it was determined that while improvements were made, specifically in data products for level 2 radiance data, striping was still prominent and east-west differences resulted in orbit to orbit inconsistencies in adjacent granules.

After the April meeting, all efforts were focused on data collected after October 30, 2000 that utilized Side B electronics. By the time we left for our MOBY replacement cruise on May 24, 2001, we had all available data match-ups processed for the Side B electronics. This included all MOBY match-ups from October 30, 2000 to March 1, 2001 and included the MOCE7 data set collected in December 2000. Utilizing this extensive data set we were able to identify prominent spectrally dependent east-west and mirror side trends in the nlw data sets. The shorter wavelengths, 412 and 443 nm, displayed a trend of lower values in the west and higher values in the east while the longer wavelengths, 488 to 667, nm displayed the opposite trend with higher values in the west and lower values in the east. When validated against MOBY and MOCE data, the shorter wavelengths were too low west of nadir and too high east of nadir with the crossover at an angle just east of nadir. The higher wavelengths displayed just the opposite validation (Figure 9). The mirror side differences were not so prominent as the east-west differences but they still resulted in noticeable stripes in the images. All these data were supplied to Miami for analysis.

When we returned from Hawaii in the middle of June, Miami had reprocessed global data from December 2, 2000 and the granules over Hawaii that provided good quality match-ups. These data had all updated algorithms and code including nlw calibrations, cloud tests, sun glint test, polarization, cross-swath linear and parabolic 'rvs’, cross scan mirror side adjustments, detector normalization and spectral adjustment. Striping was greatly reduced on these images, however, the east-west trend was still evident (Figure 10), especially when looking at orbit to orbit consistencies between adjacent granules (Figure 11). Miami said they had some ideas and were going to start over with the algorithms and within two days had new images for December 2, 2000 with reduced striping, the east-west problem fixed and with chlorophyll *a* concentrations similar to those we measured in the same area two days later (Figure 12). At this stage, we are waiting for Miami to rerun the high quality Side B granules over Hawaii with the new algorithms so we can rerun the match-ups and validate the new processing.

MOBY

MOBY continues to acquire and transmit two files per day, coincident with SeaWiFS and MODIS overpass times. MLML personnel process these files and make the data available on our MOBY home page the day after transmission. Both files are weighted to MODIS and SeaWiFS bands. This includes the MODIS total and in-band weighted data. These data are now available on the MOBY web site.

MLML personnel have begun rewriting all of the MOBY processing software. The new software is more flexible and the data files are organized more efficiently. The current algorithm used to process MOBY data will not be changed; however, when old deployments are reprocessed, the values may change slightly. Also, the MOBY homepage has been updated with frames to make viewing data easier. Starting with MOBY216, MOBY data are processed with the new software. Old deployments will be reprocessed as time allows. Currently, MOBY215 and 214 data have been reprocessed.

MOS/SIS

Mike Feinholz continues to process data from instrument calibrations and from shipboard MOS and SIS profiles using MATLAB programs customized at MLML. Eleven profiles were performed during the MOCE-8 cruise, plus 3 profiles during 2 time-series solar-elevation experiments during MOBY-L69 in June. Profiles are typically coincident with MOBY profiles and/or SeaWiFS and MODIS observations. MOS water-leaving radiances are convolved with SeaWiFS and MODIS spectral band responses for integration with our bio-optical data base (see Appendix 4 for a MOS station summary).

During the reporting period, MLML personnel developed a suite of low level Matlab functions to control MOS and acquire spectral scans (Appendix 5). These programs use the Matlab Instrument Control Toolbox introduced with the latest version of Matlab. The overall goal of this work is to replace the obsolete VAX work stations that have been used since MOBY work started. The Graphical User Interface (GUI) was developed to implement the lower level functions. The refined control and data assimilation functions enable command line control of MOS via a laptop PC - thus providing, for the first time, a system to replace the VAX work station. The field-test of the new software is scheduled during the next MOBY deployment cruise in late September.

FOS

The data processing software for the FOS was completed. The software allows the user to create system response files, dark scan files, process and error check the data, and calculate derived products. The Graphical User Interfaces (GUI's) allow users with limited MATLAB experience to easily and interactively check the data. Users with minimal experience with MATLAB have given the processing software high praise. Non-GUI functions process the data following MLML radiometric protocols. In addition to processing the data, HTML pages are created automatically allowing the user to view the processed data easily.

METEOROLOGICAL / ATMOSPHERIC DATA

All MOCE-7 and MOCE-8 ancillary data, which include wind speed, barometric pressure, ship position, flow rate, humidity, beam atteuation, temperature and salinity, have been processed.

Atmospheric data collected during the last three characterization cruises (MOCE-6, MOCE-7, and MOCE-8) were processed and analyzed. Data were collected using two types of instrumentation systems: a Hand-Held Contrast Reduction Meter (HHCRM) and hand-held multi-band sun photometers (MICROTOPS II). Whenever stable atmospheric conditions occurred, multiple measurements of the solar beam were made, then the Langley technique was used to obtain the extraterrestrial flux. Figure 13 shows the Langley calibrations obtained on December 6, 2000 during the MOCE-7 cruise. The extraterrestrial solar irradiance was used to calculate total optical depth for each oceanographic station. To obtain the aerosol optical depth (AOT), total optical depth was used with computed optical depth due to molecular scattering (Rayleigh optical depth), and absorption by ozone. Figure 14 depicts computed AOT for Station 4 during the MOCE-7 cruise using these two types of instrumentation..

BIO-OPTICAL DATABASE

The work is continuing on the comprehensive database which includes pigment, total suspended material and radiometric data from the CZCS Era to present. MOCE-7 & 8 cruise data are being added to the database.

PIGMENTS

Pigment data for the MOCE-7 cruise were processed using two calibration methods. The first is using the Fluorometrically derived Chlorophyll, the second is using HPLC pigments provided by CHORS. The HPLC pigment samples from MOCE-8 cruise were processed in April. In addition, 12 HPLC samples collected during the MOBY-L65 Mooring cruise (7-8 February 2001) were also processed with the MOCE-8 data. The pigment data from these two cruises graphically depicted in Figure 12a, b and c.

PUBLICATIONS AND MEETINGS

MLML personnel completed the MOCE-6 Radiometric and Oceanographic profiling Observations Technical Publication 01-1. The technical publication includes SeaBird CTD, Satlantic SeaWiFS Profiling Multichannel Radiometer (SPRM), and TSM/POC filtration data.

A paper "Development of a Consistent Multi-Sensor Global Ocean Color Time Series" by R.A.Barns, D.K.Clark, W.E.Esaias, G.S.Fargion, G.C.Feldman, and C.R.McClain was presented at the International Workshop on Geo-Spatial Knowledge Processing for Natural Resource Management in Varese, Italy, June 28-29 (Appendix 6).

A paper "An emerging ground-based aerosol climatology: Aerosol Optical Depth from AERONET" by B.N.Holben, D.Tarne, A.Smirnov, T.F.Eck, I Slutsker, N.Abuhassan, W.W.Newcomb, J.Schafer, B.Chatenet, F.Lavenue, Y.J.Kaufman, J.Vande Castle, A Setzer, B.Markhman, D.Clark, R.Frouin, R.Halthore, A.Karnieli, N.T.O'Neil, C.Pietras, R.T.Pinker, K.Voss, and G.Zibordi was accepted for publication in J.Geophys. Res., 2000.

Dennis Clark, Mike Ondrucek, and Marilyn Yuen attended a MODIS Team Meeting in Columbia, MD, January 22 - 26. 2001.

Dennis Clark and Mike Ondrucek attended a MODIS Ocean Team Meeting in Miami, FL, April 2 - 6, 2001.

Dennis Clark, Mark Yarbrough, and Mike Feinholz traveled to Gaithersburg, MD, April 24 - May 11, to work with NIST personnel on Stray Light Verification.

Stephanie Flora presented her thesis "Comparison of a simple marine irradiance model to marine optical buoy measurements" to the Faculty of Califprnia State University, Stanislaus through MLML in April, 2001.

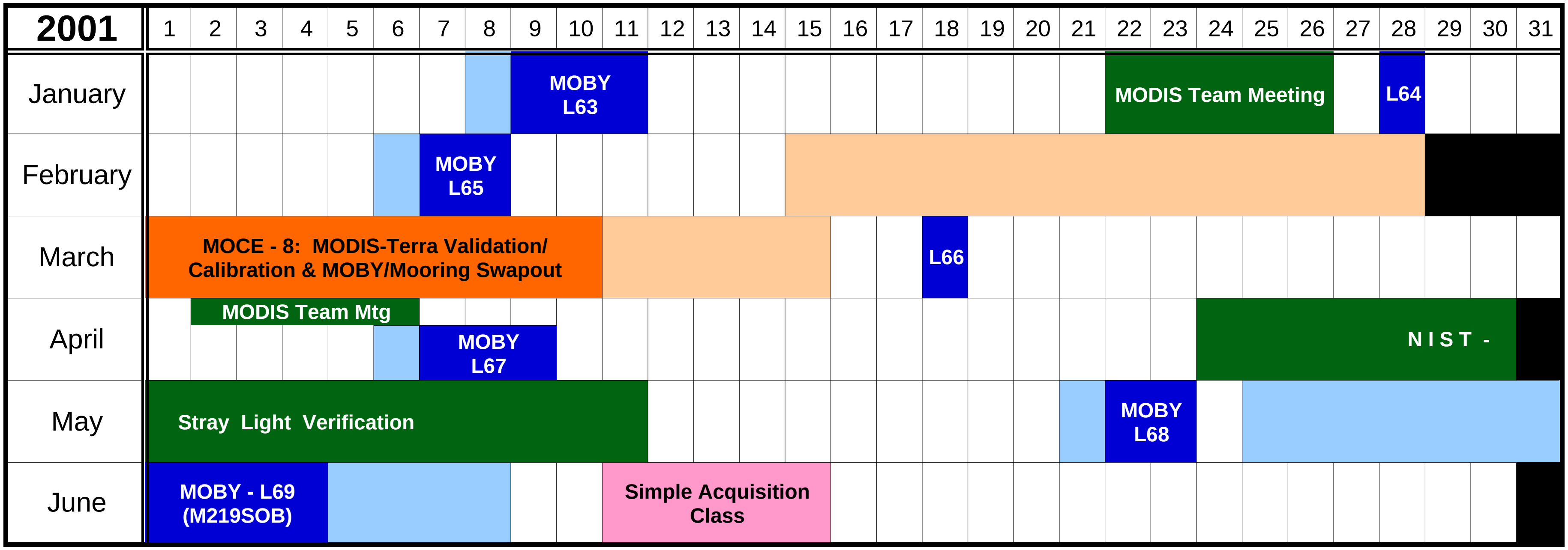
MOBY CONTRACTS

During the past six months, a new contract for the University of Hawaii Shore Support was initiated. This contract allows the MOBY project to utilize space at the UH Marine Facility.

The University of Hawaii Machine Shop contract was extended for an additional 12 months. This contract provides services in fabrication and maintenance of the buoy.

A new QSS service contract was initiated for Mike Feinholz, Mark Yarbrough, Mike Ondrusek, and Larisa Koval

MOCE Team Activities



2001	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
January								🟦	MOBY L63													MODIS Team Meeting						L64			
February						🟦	MOBY L65								🟧														⬛		
March	MOCE - 8: MODIS-Terra Validation/ Calibration & MOBY/Mooring Swapout										🟧							L66													
April		MODIS Team Mtg				🟦	MOBY L67																	NIST -							⬛
May	Stray Light Verification																				🟦	MOBY L68			🟦						
June	MOBY - L69 (M219SOB)				🟦						Simple Acquisition Class																				⬛

Figure 1.xls

FIGURE 2

FIGURE 3

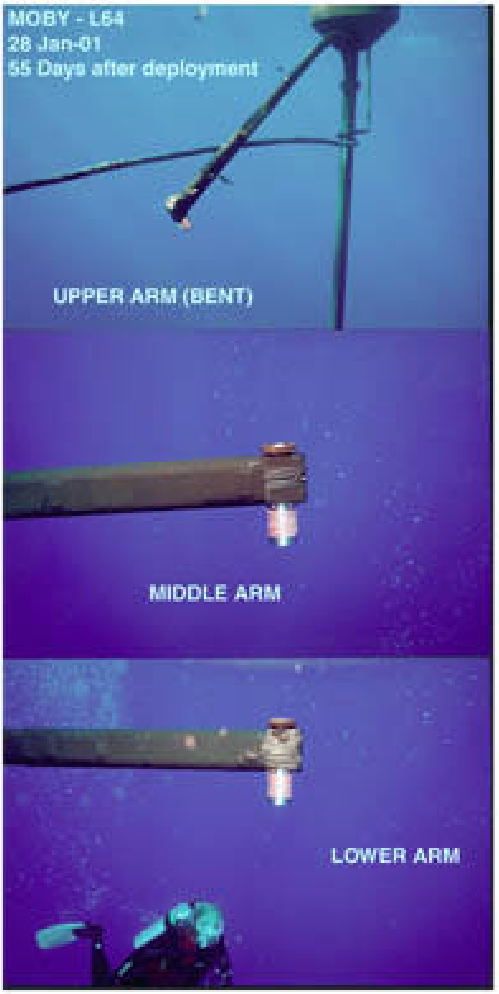

MOBY - L64
28 Jan-01
55 Days after deployment
UPPER ARM (BENT)
MIDDLE ARM
LOWER ARM

FIGURE 4

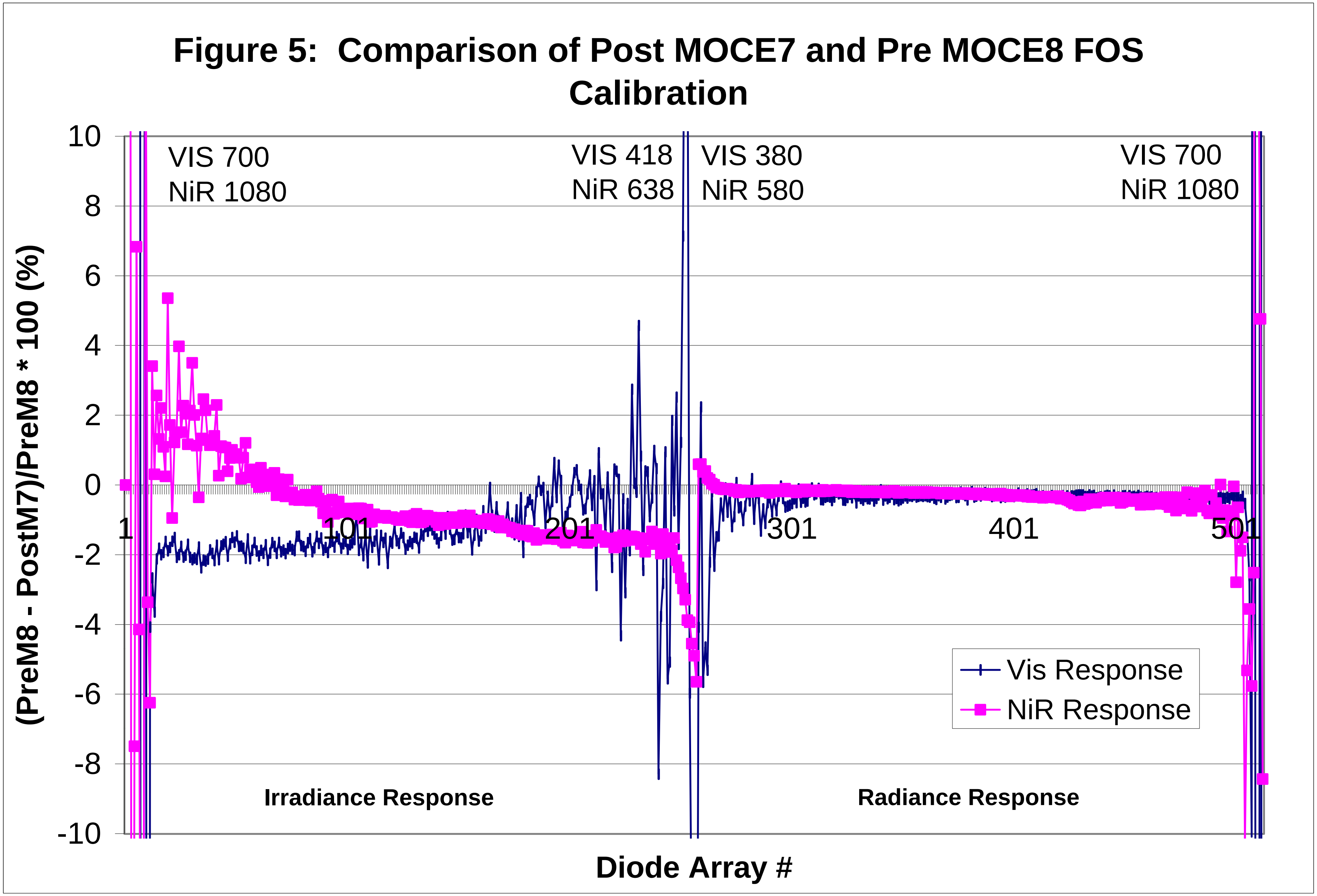
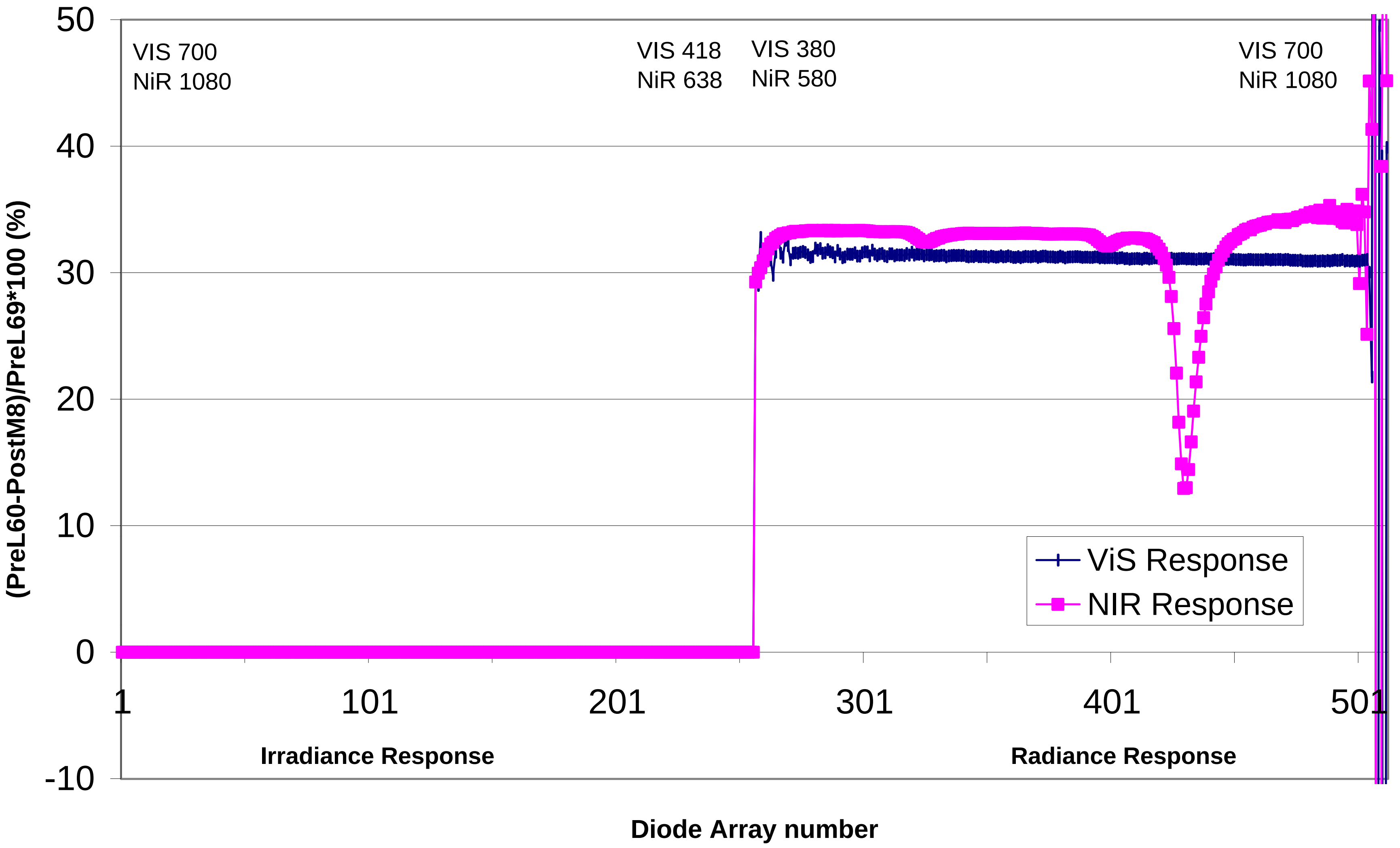


Figure 5: Comparison of Post MOCE7 and Pre MOCE8 FOS Calibration
(PreM8 - PostM7)/PreM8 * 100 (%)
10
8
6
4
2
0
-2
-4
-6
-8
-10
1
101
201
301
401
501
VIS 700
NiR 1080
VIS 418
NiR 638
VIS 380
NiR 580
VIS 700
NiR 1080
Vis Response
NiR Response
Irradiance Response
Radiance Response
Diode Array #

Figure 6: Comparison of Pre L-69 and Post MOCE 8 FOS Calibration



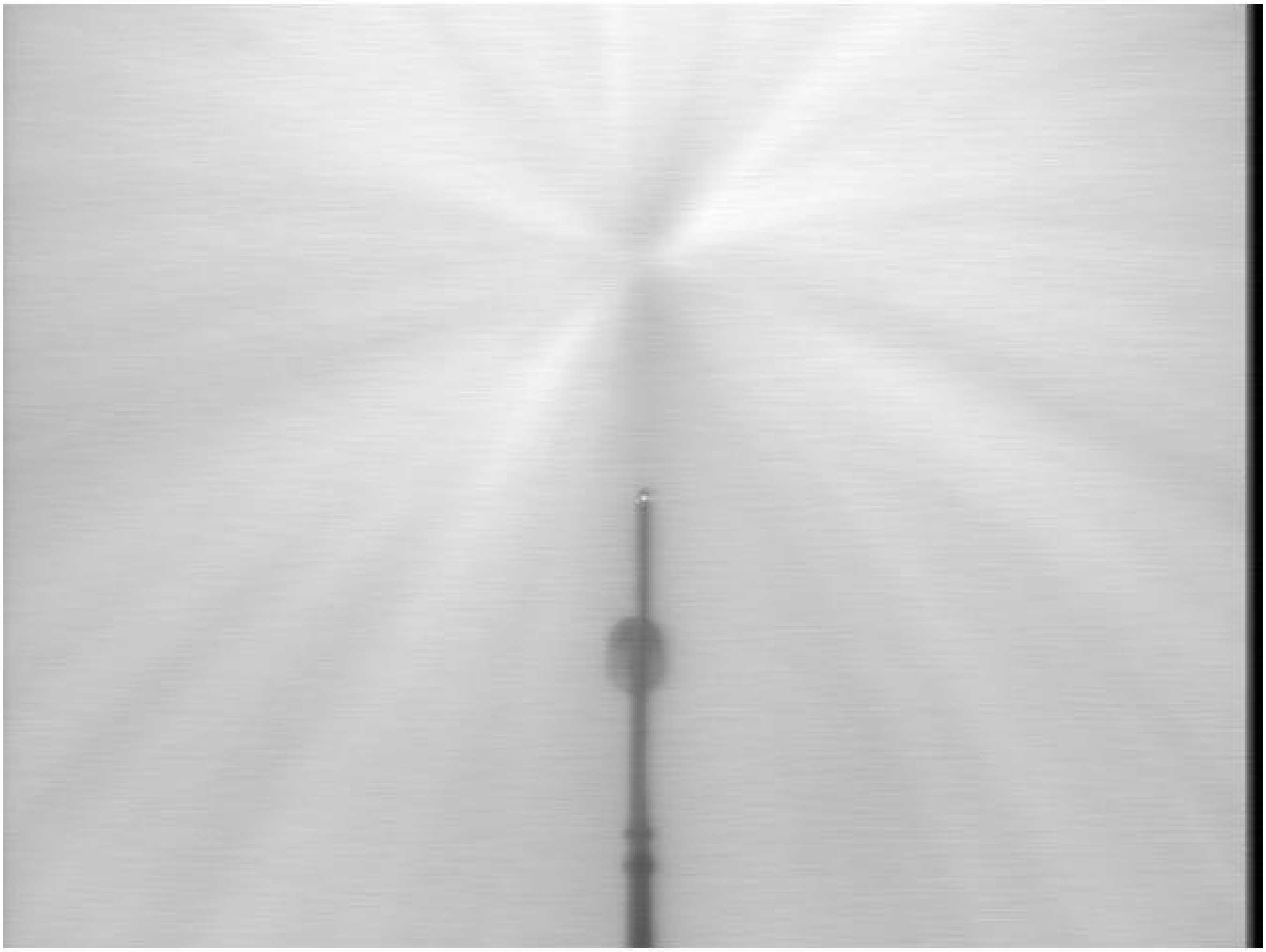


Figure 7. Example of WARS image collected off MOBY's top arm March 7, 2001 at noon.

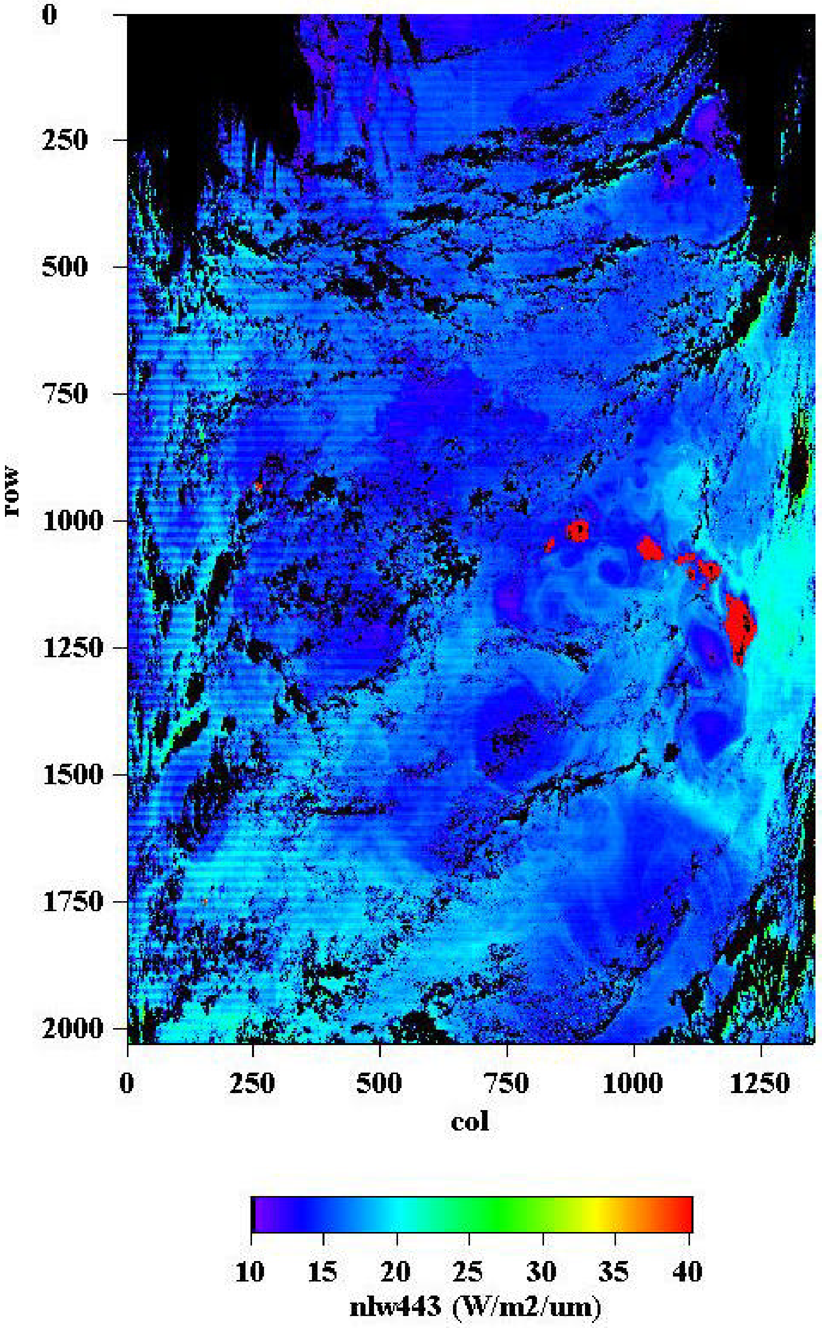
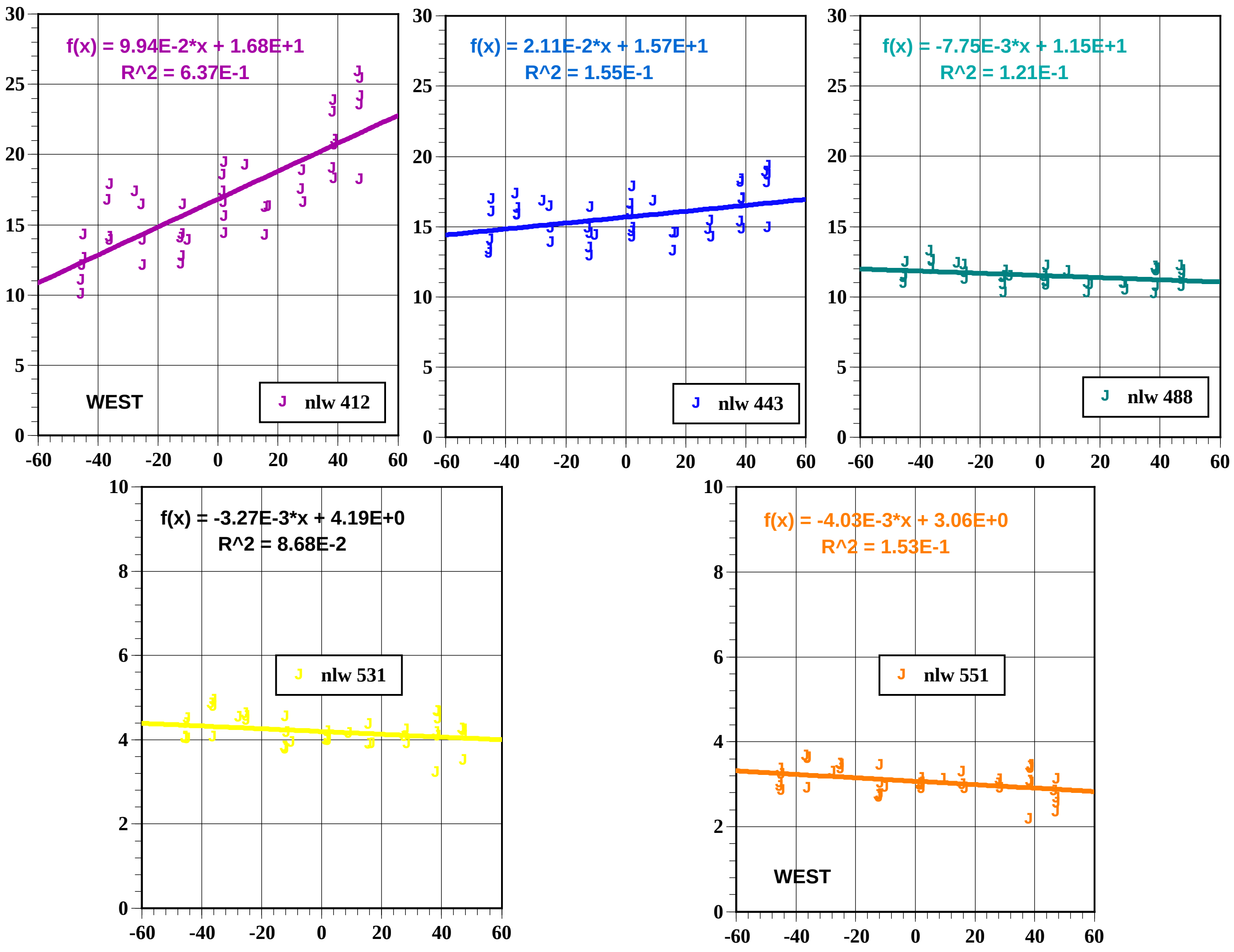
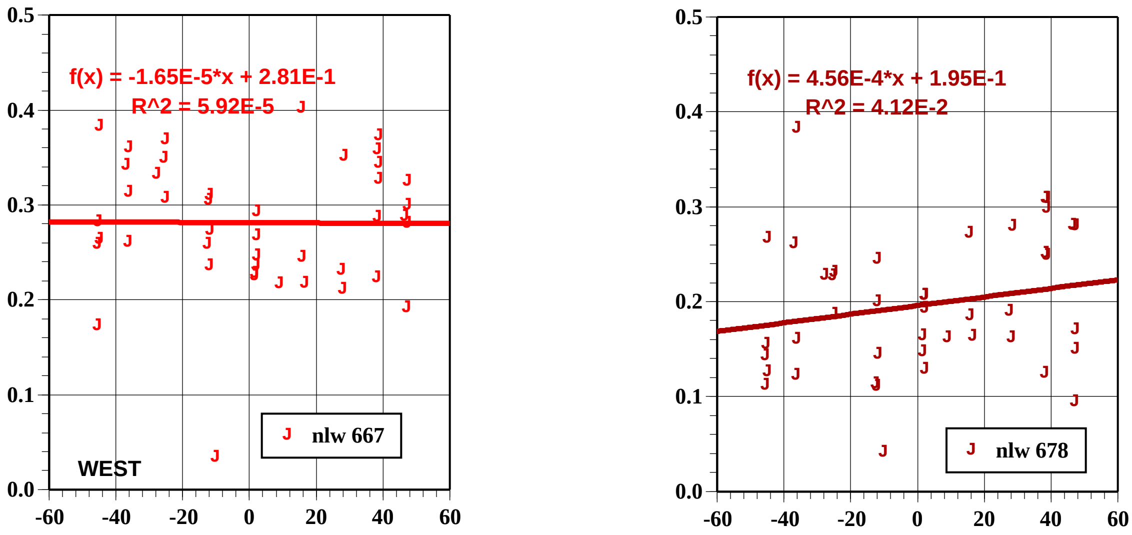


Figure 8. Normalized water leaving radiance at 443 nm for the 2140 hr granule over Hawaii on December 1, 2000. Image processed by GSFC on 1/24/01 at 2013 hr.



f(x) = 9.94E-2*x + 1.68E+1
R^2 = 6.37E-1
WEST
J nlw 412
f(x) = 2.11E-2*x + 1.57E+1
R^2 = 1.55E-1
J nlw 443
f(x) = -7.75E-3*x + 1.15E+1
R^2 = 1.21E-1
J nlw 488
f(x) = -3.27E-3*x + 4.19E+0
R^2 = 8.68E-2
J nlw 531
f(x) = -4.03E-3*x + 3.06E+0
R^2 = 1.53E-1
J nlw 551
WEST
0
5
10
15
20
25
30
0
2
4
6
8
10
-60
-40
-20
0
20
40
60

Figure 9



Least-Squares Equations

MODIS nLw 412

f(x) = 9.94E-2*x + 1.68E+1
R^2 = 6.37E-1

MODIS nLw 443

f(x) = 2.11E-2*x + 1.57E+1
R^2 = 1.55E-1

MODIS nLw 488

f(x) = -7.75E-3*x + 1.15E+1
R^2 = 1.21E-1

MODIS nLw 531

f(x) = -3.27E-3*x + 4.19E+0
R^2 = 8.68E-2

MODIS nLw 551

f(x) = -4.03E-3*x + 3.06E+0
R^2 = 1.53E-1

MODIS nLw 667

f(x) = -1.65E-5*x + 2.81E-1
R^2 = 5.92E-5

MODIS nLw 678

f(x) = 4.56E-4*x + 1.95E-1
R^2 = 4.12E-2

Figure 9 Cont.

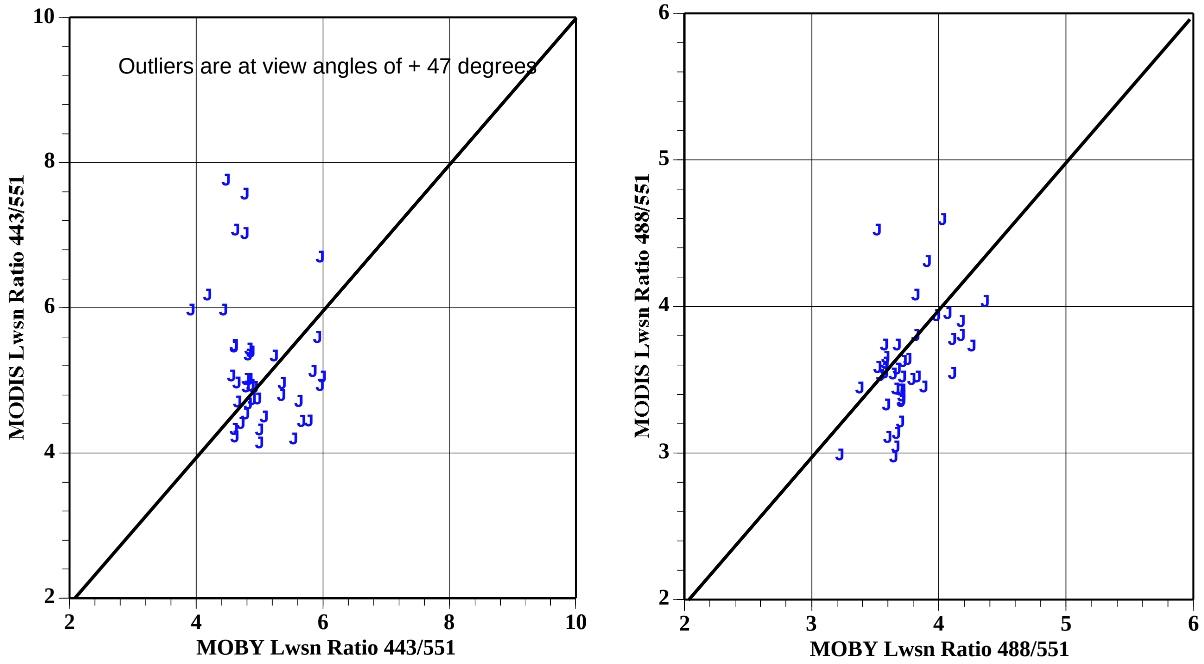


Figure 9 Cont.

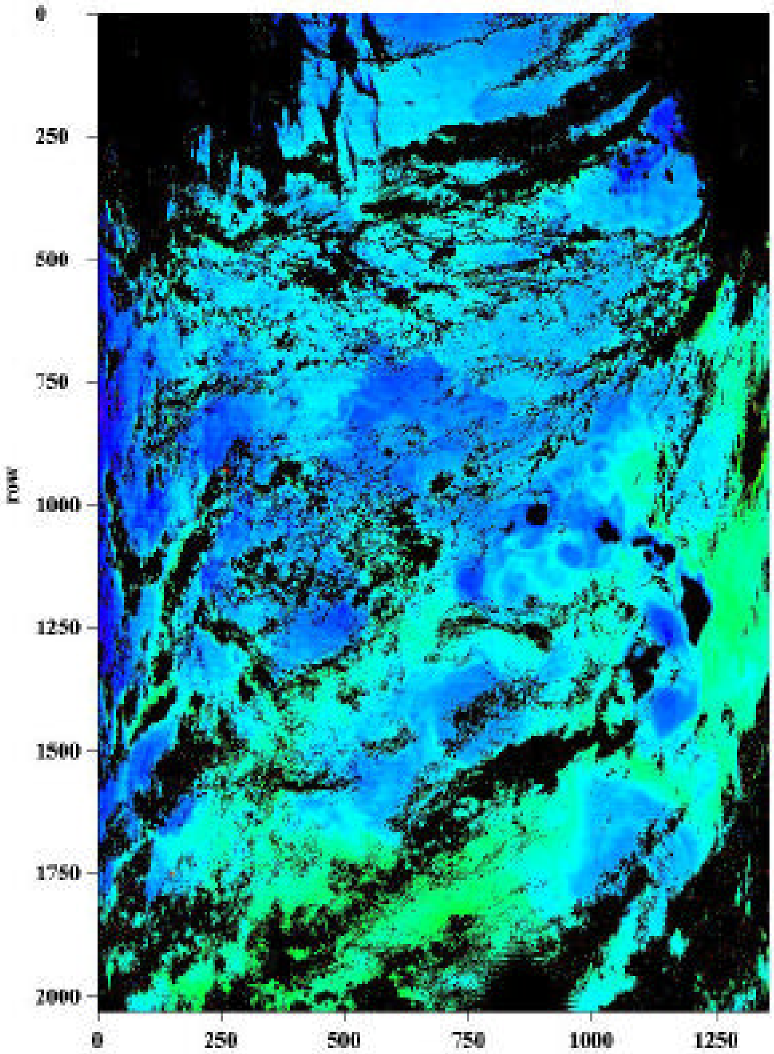


Figure 10. Normalized water leaving radiance at 443 nm for the 2140 hr granule over Hawaii on December 1, 2000. Image processed by RSMAS, University of Miami on 6/20/01.

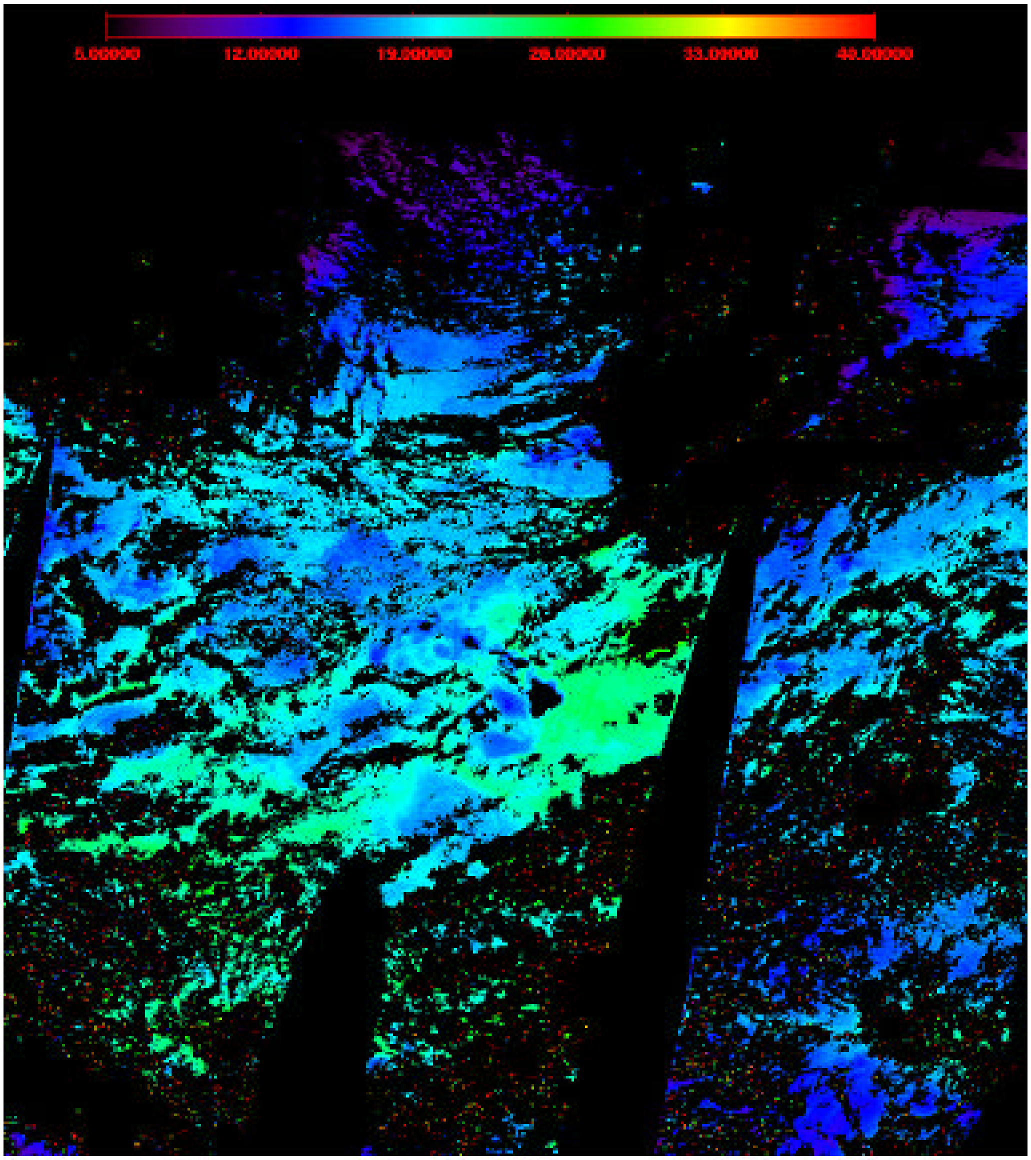


Figure 11. Portion of global image over Hawaii of Normalized water leaving radiance at 443 nm. Granule to granule inconsistencies are noticeable across gaps between granules. Processed at RSMAS, University of Miami on 6/20/01 (see Fig. 10).

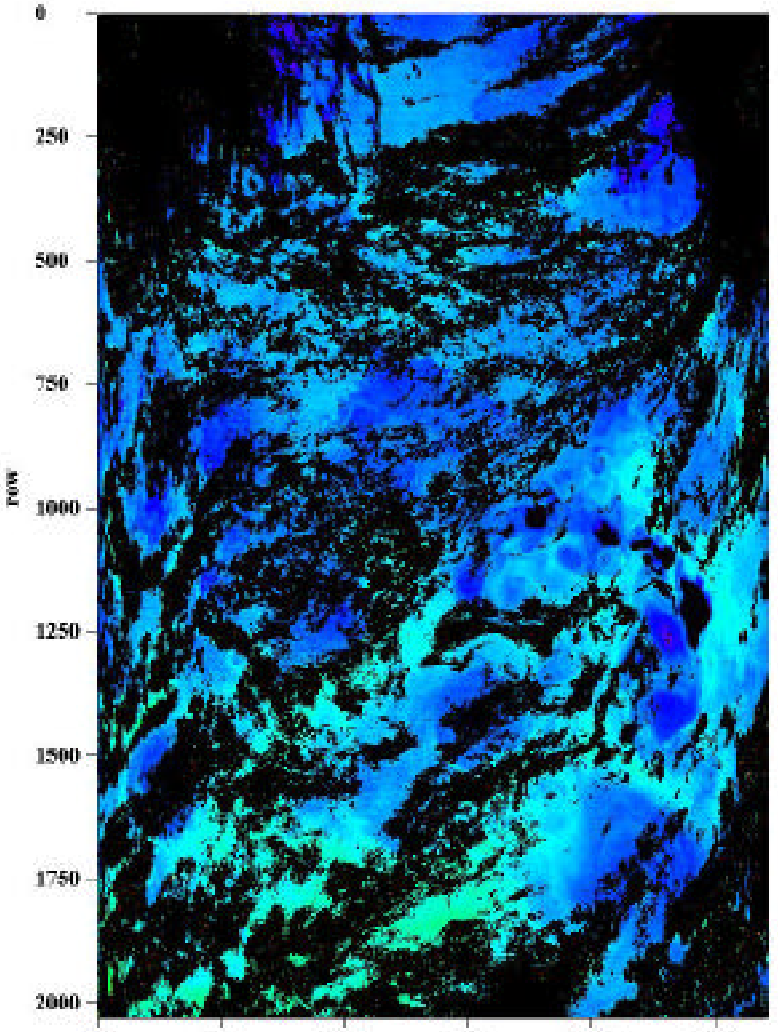
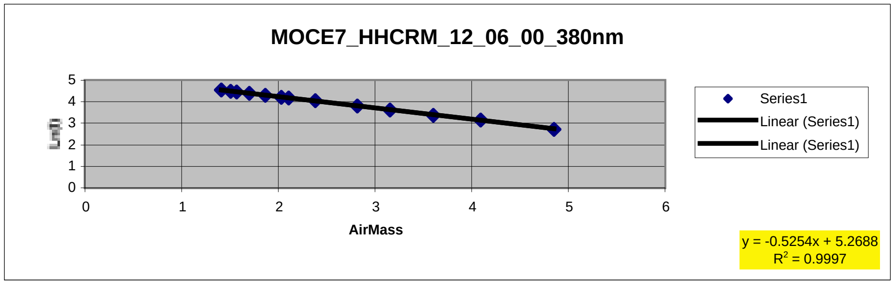
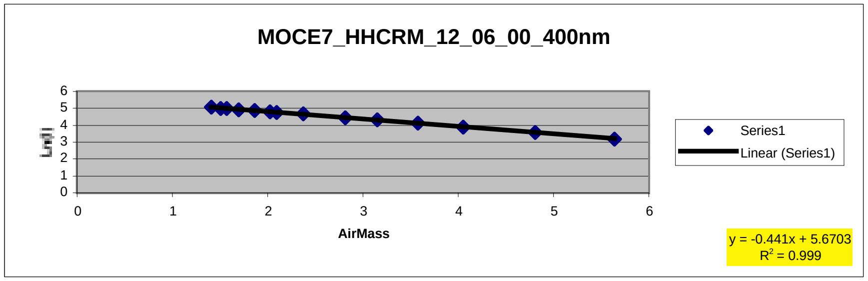
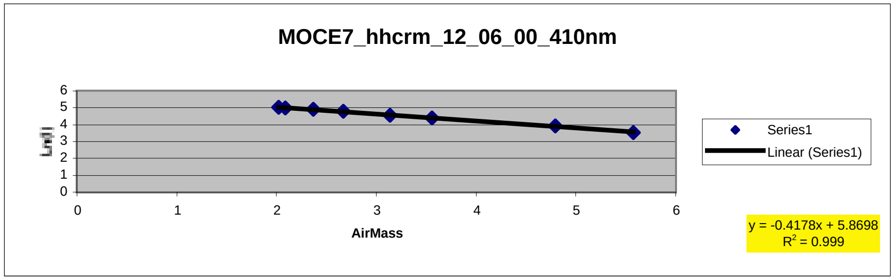


Figure 12. Normalized water leaving radiance at 443 nm for the 2140 hr granule over Hawaii on December 1, 2000. Image processed by RSMAS, University of Miami on 6/22/01.

FIGURE 13. LANGLEY CALIBRATIONS MOCE-7 12/06/2000


MOCE7_HHCRM_12_06_00_380nm


MOCE7_HHCRM_12_06_00_400nm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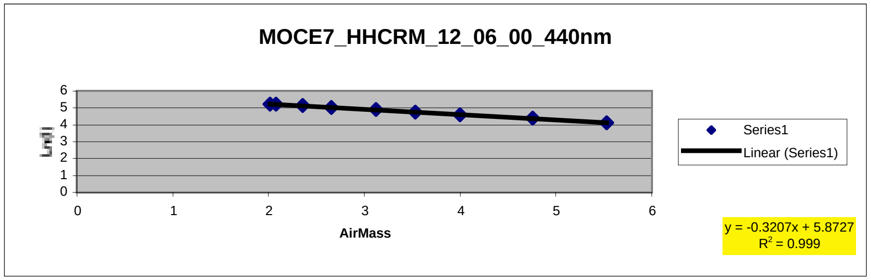
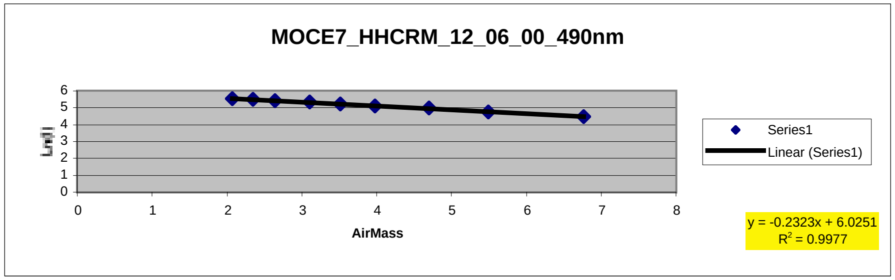
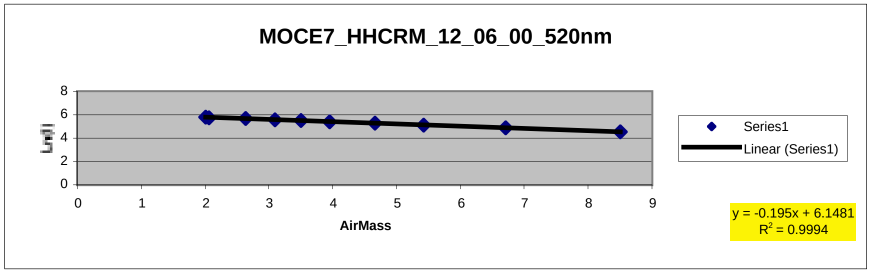
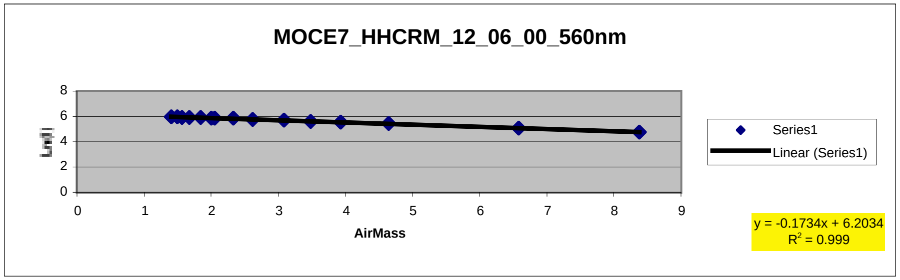

MOCE7_HHCRM_12_06_00_440nm


MOCE7_HHCRM_12_06_00_490nm


MOCE7_HHCRM_12_06_00_520nm


MOCE7_HHCRM_12_06_00_560nm

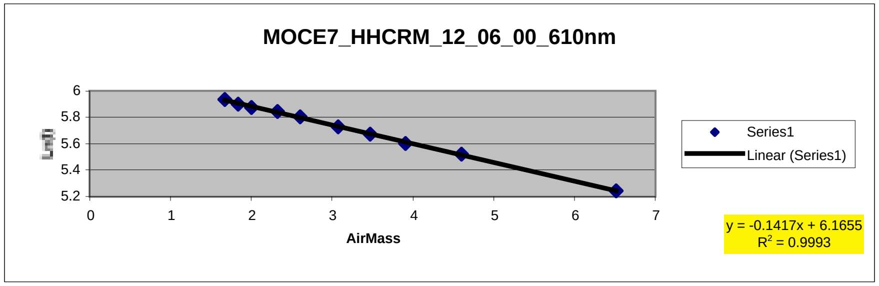
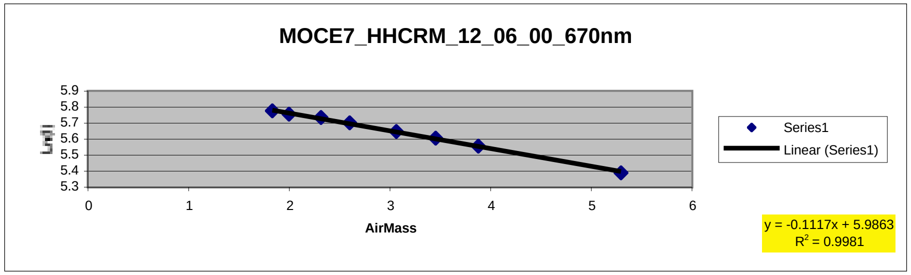

MOCE7_HHCRM_12_06_00_610nm

FIGURE 13 Continue

FIGURE 13 Continue


MOCE7_HHCRM_12_06_00_670nm

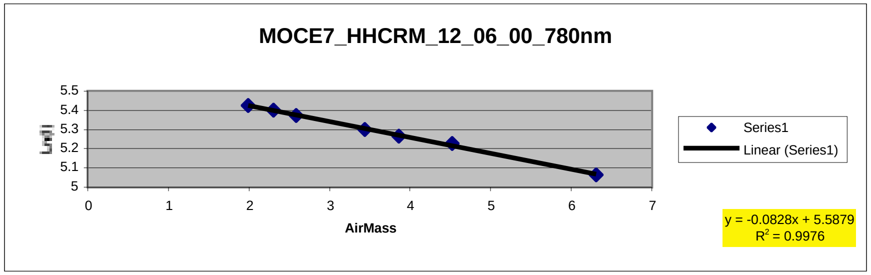
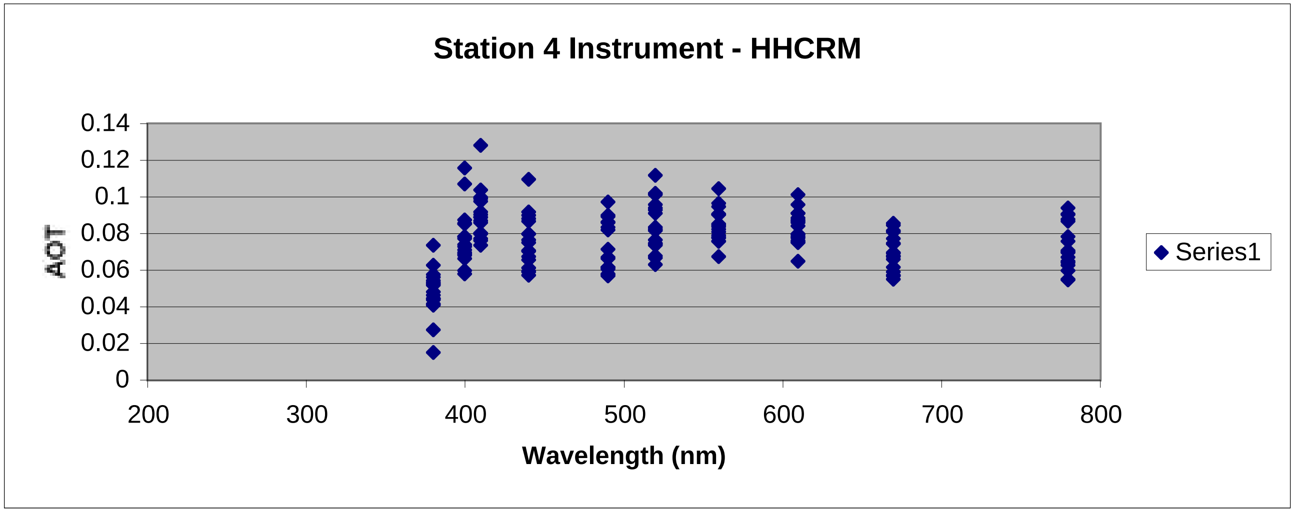
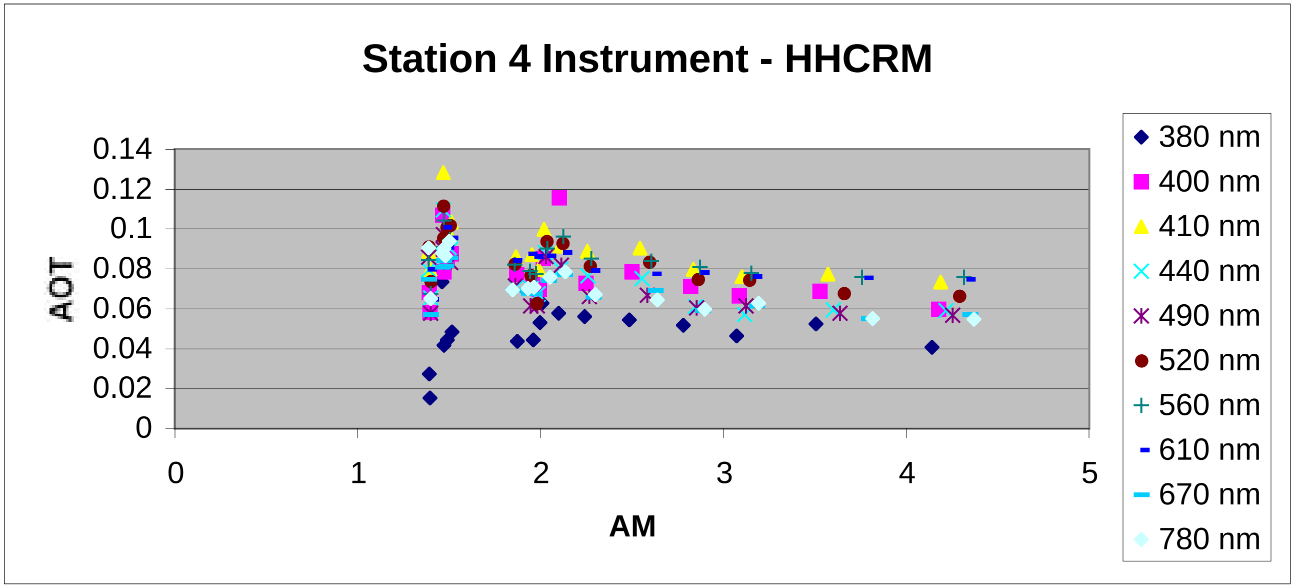
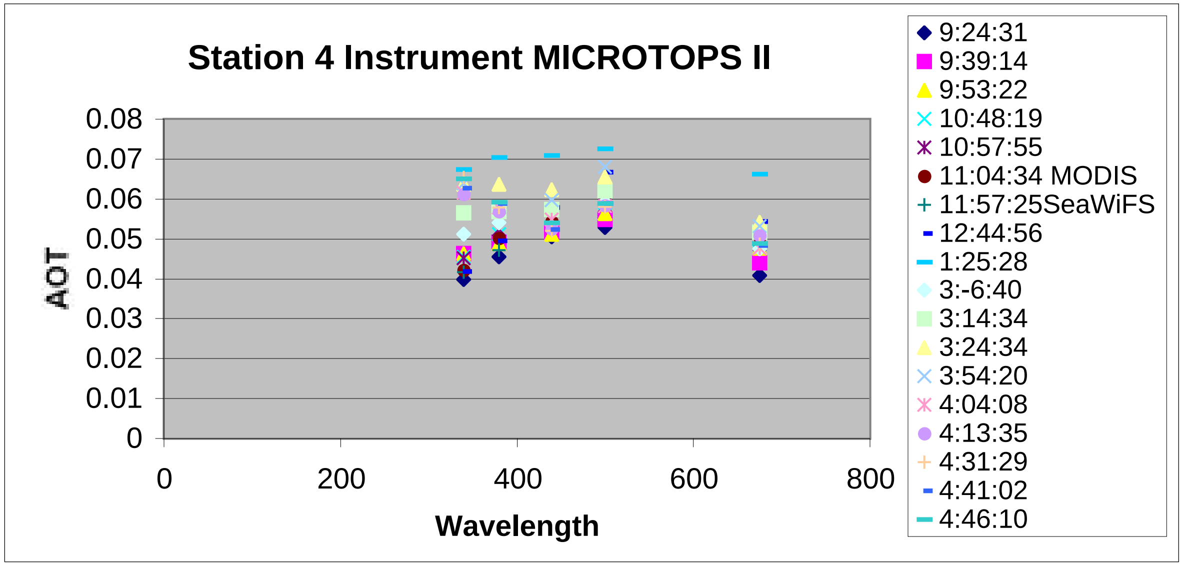
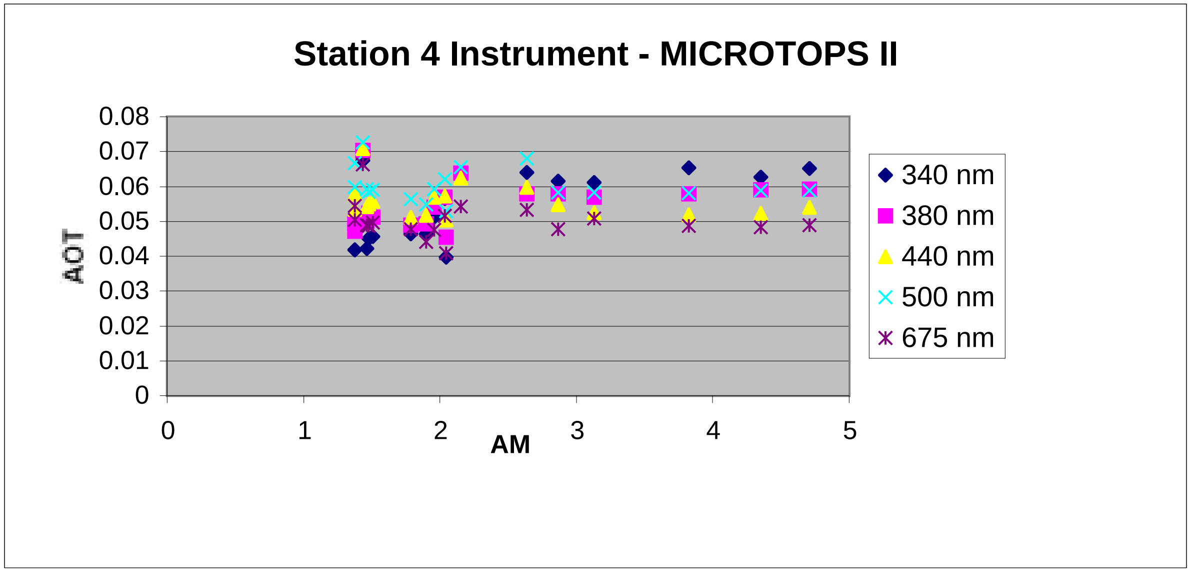

MOCE7_HHCRM_12_06_00_780nm

Figure 14. Total optical depth observed during Station #4 on MOCE-7






Station 4 Instrument MICROTOPS II
AOT
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
200
400
600
800
Wavelength
◆ 9:24:31
■ 9:39:14
▲ 9:53:22
× 10:48:19
✻ 10:57:55
● 11:04:34 MODIS
+ 11:57:25SeaWiFS
- 12:44:56
- 1:25:28
◆ 3:-6:40
■ 3:14:34
▲ 3:24:34
× 3:54:20
✻ 4:04:08
● 4:13:35
+ 4:31:29
- 4:41:02
- 4:46:10


Station 4 Instrument - MICROTOPS II
AOT
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1
2
3
4
5
AM
◆ 340 nm
■ 380 nm
▲ 440 nm
× 500 nm
✻ 675 nm

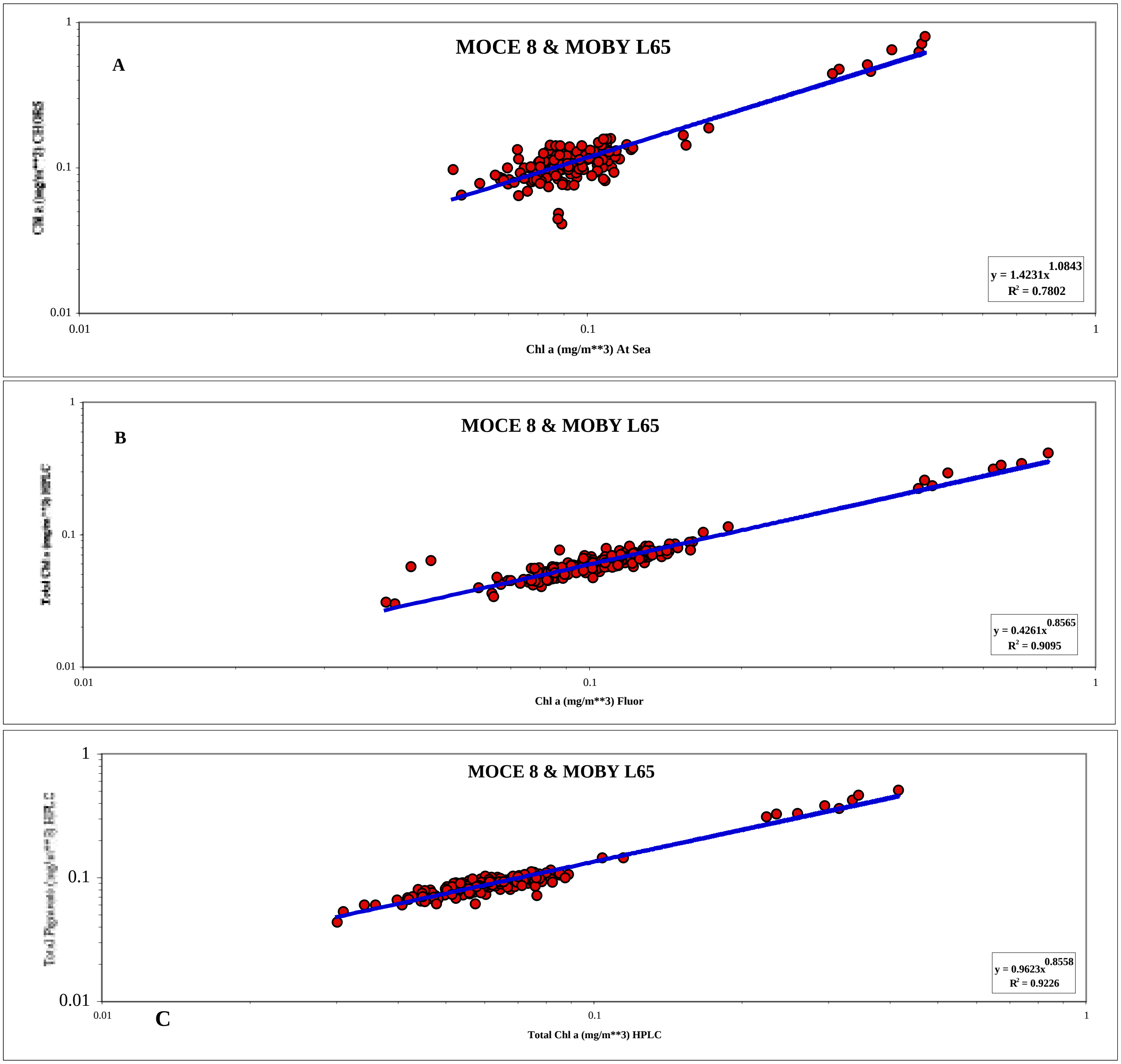


Figure 15. Log-linear regression models predicting fluorometrically determined chlorophyll *a* measured at CHORS from fluorometrically measured chlorophyll *a* at sea (A), total chlorophyll *a* measured by HPLC from fluorometrically determined chlorophyll *a* (B) and total accessory pigments from total chlorophyll *a* (C) for MOCE 8 and L65 Cruises.

INTRODUCTION

The eighth Marine Optical Characterization Experiment (MOCE-8) occurred 28 February - 9 March 2001 near the Hawaiian island Lanai on the University of Hawaii's research vessel (R/V) Ka'imikai-O-Kanaloa. During this cruise, nine bio-optical stations were occupied, and the Marine Optical Buoy (MOBY) and the meteorological mooring buoy were exchanged.

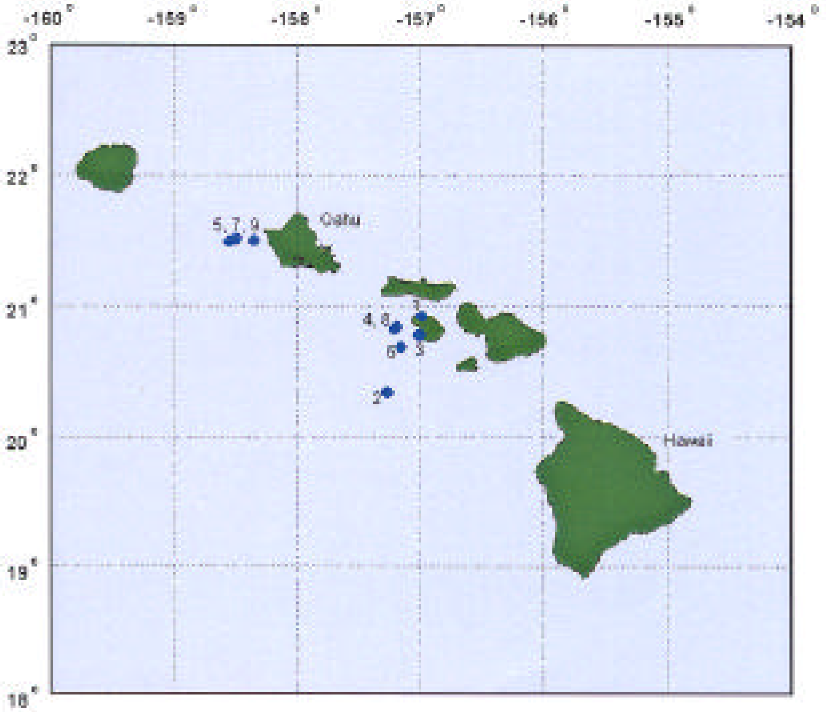


Figure 1. MOCE-8 station locations, 28 February - 9 March 2001.

The objective of this cruise was to increase the number of data sets available for the validation and calibration of MODIS and SeaWiFS imagery. The data collected during this cruise provided more radiometric characterizations and spatial variability of water-leaving radiances and atmospheric transmittances concurrent with ocean color sensor observations.

Six of the nine MOCE-8 stations had a MODIS or SeaWiFS overpass within 200 nm of MOBY. Satellite overpasses and distances are summarized in Table1.

Date (HST)	Julian Day	Station		MODIS Overpass			SeaWIFS Overpass		
		#	Name	Time (HST)	Dist (nm)	Orbit #	Time (HST)	Dist (nm)	Orbit #
28 Feb 01	59	1	Kalohi Channel	11:36	**188**	6385.65	12:16	373	19076.65
02 Mar 01	61	2	Pala'oa Point	11:24	**20**	6414.67	12:03	546	19105.67
03 Mar 01	62	3	Kaumalapau Harbor	12:06	607	6429.68	12:46	**49**	19120.67
04 Mar 01	63	4	MOBY Mooring 1	11:11	**150**	6443.69	13:29	634	19135.68
05 Mar 01	64	5	Port Wai'anae 1	11:54	441	6458.69	12:45	**123**	19149.69
06 Mar 01	65	6	South of MOBY	10:59	319	6472.71	13:16	465	19164.70
07 Mar 01	66	7	Port Wai'anae 2	11:42	274	6487.71	12:21	295	19178.71
08 Mar 01	67	8	MOBY Mooring 2	10:47	489	6501.73	13:04	296	19193.71
09 Mar 01	68	9	Port Wai'anae 3	11:30	**106**	6516.73	12:09	468	19207.73

Table 1. Summary of ocean color satellite overpass times and distances from MOBY during MOCE-8. Dates and times are in Hawaiian Standard Time (HST). GMT = HST + 10.

MATERIALS AND METHODS

The data sets collected during MOCE-7 and MOCE-8 are separated into four categories: bio-optical, biological, physical, and meteorological. A brief description of instrumentation and data collection and analysis procedures used for each data set follows.

Bio-Optical Data Sets

Six bio-optical data sets were collected during MOCE-7. Upwelled radiance and downwelled irradiance data at specific depths were obtained by two instruments working in tandem - the Marine Optical System (MOS) and the Surface Incident Spectrometer (SIS). Upwelled radiance and downwelled irradiance profiles were achieved with Satlantic's SeaWiFS Profiling Multichannel Radiometer (SPMR) and its accompanying SeaWiFS Multichannel Surface Reference (SMSR). Just below sea surface upwelling radiance distributions were measured with a radiance distribution camera. Instrument self-shading experimental data were collected with a Fiber Optic Spectrometer (FOS) system. Phytoplankton Absorption (A_{ph}) data were attained for discrete water samples with a diode array spectrophotometer and an integrating sphere, and Colored Dissolved Organic Material (CDOM) spectra were collected with just the spectrophotometer.

MOS and SIS. The Marine Optical System (MOS) is a submersible dual band radiometer measuring 1024 channels of spectral upwelled radiance (L_u) and downwelled irradiance (E_d) in the spectral region 340-950 nm with a resolution of less than 1 nm. The second generation MOS (MOS2) incorporates relay optics built by Research Support Instruments, Inc. (RSI) and two custom designed American Holographic VS-10 single holographic grating spectrographs. A four-position Geneva motor positions a mirror to select a beam from the upwelling or downwelling ports, the blue and red LEDs and an incandescent lamp, or the dark position. The beam impinges on the Corion dichroic "water" mirror. The red (540-950 nm) portion is transmitted to another folding mirror and through a blue rejection filter onto the shutter. The blue (340-650 nm) portion of the input beam reflects off the water mirror on to a shutter mounted before the entrance slit on the second spectrograph.

The detectors are Photometrics Series 200 CCD camera systems, with Tektronics 512 by 512 pixel CCD detectors. CCD detectors are maintained at about minus 40 degrees Celsius by thermo-electric coolers and are controlled by Photometrics electronics with 16-bit digitization. MOS incorporates an Onset Computers Tattletail Model 7 MC68332 microprocessor with MLML FORTH operating system which communicates with a shipboard deck unit via serial data interface for real-time data transfer and control. During field data acquisition MOS is powered by an external 12 volt lead acid rechargable battery pack.

The Marine Optical System also incorporates a suite of ancillary sensors. External water temperature and pressure, as well as instrument X and Y tilt, system current, and coolant flow are digitized with 16-bit precision. MOS has several internal 16-bit thermistors for: the blue and red arrays, blue and red CCD heads, pressure transducer, and reference diode platform. Blue and red CCD heaters and calibration diodes are monitored at 16-bit A/D while 12-bit A/D monitors include: system voltage, TT7 temperature, case temperature, and internal humidity.

The Surface Incident Spectrometer (SIS) measures 38 bands of surface-incident irradiance (E_s) in the spectral range 370-725 nm with a bandpass of about 9 nm. SIS used an American Holographic MS-10 spectrograph and DA-38 detector module with Hamamatsu diode array detector contained in a waterproof PVC housing. An Onset Computers Tattletail Model 7 MC68332 computer with Moss Landing Marine Laboratories (MLML) FORTH controlled Data Translations 16-bit A/D with 1, 10, 100, and 500 X gain. SIS also included an internal temperature sensor and precision voltage reference source. Data telemetry was accomplished via serial interface to a shipboard deck unit and acquisition computer.

MOS and SIS were calibrated before and after MOCE-7 for absolute radiometric response, and were monitored during the cruise by a stable radiance source. E_d and E_s sensors were calibrated by a Gamma Scientific 5000 system with 1000 Watt FEL F-453, which had a 29 Jul 1998 National Institute of Standards and Technology (NIST) calibration. Wavelength calibrations were via Oriel HgA and Ne Spectral Calibration "Pen" lamps. The MOS L_u sensor response was determined by an Optronic Laboratories OL420 radiance source with a 17 Feb 2000 Optronic calibration. The OL420 was also used to calibrate MOS integration time and to check CCD bin factor accuracy. Radiance and irradiance calibration sources were monitored during all laboratory experiments by NIST Single Channel Multi-Purpose Sensors (SCAMPS). Once aboard the R/V Ka'imikai-O-Kanaloa, radiometric stability was monitored by scanning a Gamma Scientific RS-10 portable radiance source at appropriate intervals.

MOS data were collected after the R/V Ka'imikai-O-Kanaloa was stopped on station about three hours before local noon, and the spectroradiometer tetrahedron was deployed by allowing it to drift away from the ship. MOS was attached to an electric winch at the apex of the tetrahedron and was lowered to successive depths where it made repeated spectral scans. Upwelled radiance and downwelled irradiance data were obtained sequentially as a group of two dark (shuttered) scans, five radiance or irradiance scans followed by two dark scans constituting a "scan set". Depending upon atmospheric conditions and wave roughness, between three and ten scan sets were collected at each depth during a MOS optical profile.

The SIS was mounted on a gimbal attached to an instrument platform above all ship shadowing obstructions. SIS was operated during daylight hours at a ten minute interval except during in-water radiometer operations, then SIS made spectral scans at one minute intervals. SIS typically averaged 10 measurements internally, and a scan set included two dark scans, followed by five irradiance scans and another two dark scans.

Data acquired from MOS and SIS were processed during and after the cruise via MLDBASE modules running under MATLAB version 5.3 on a Windows 98 PC. Signal-to-Noise ratio was calculated from raw spectra and the calibration response multiplier was applied to dark-adjusted spectra. Data were quality controlled to select final output spectra by noting Signal:Noise, instrument inclination and depth range, cloud cover as recorded by the "sky" camera, and variability of surface-incident irradiance. MOS spectra were binned at 8 wavelengths by applying SeaWiFS pre-launch in-band "piece part" spectral responses. MOS and SIS data formats are summarized in Table 2.

MOS_LU.TXT

- 14 columns by 95 rows of 8-Digit ASCII data
- L_u (uW/cm^2/sr) binned via SeaWiFS In-Band "Piece Part" Spectral Responses at eight wavelengths - 412, 443, 490, 510, 555, 670, 765, 865 nm:

Col 01 = Station (#)
Col 02 = Latitude (fractional degrees, +North)
Col 03 = Longitude (fractional degrees, +West)
Col 04 = Julian Day (GMT, 2000)
Col 05 = Time (GMT fractional hour)
Col 06 = Depth (dbar)
Col 07 = Lu(412 nm)
•
•
•
Col 14 = Lu(865 nm)

MOS_ED.TXT

- 14 columns by 86 rows of 8-Digit ASCII data
- E_d (uW/cm^2) binned via SeaWiFS In-Band "Piece Part" Spectral Responses at eight wavelengths - 412, 443, 490, 510, 555, 670, 765, 865 nm:

Col 01 = Station (#)
Col 02 = Latitude (fractional degrees, +North)
Col 03 = Longitude (fractional degrees, +West)
Col 04 = Julian Day (GMT, 2000)
Col 05 = Time (GMT fractional hour)
Col 06 = Depth (dbar)
Col 07 = Ed(412 nm)
•
•
•
Col 14 = Ed(865 nm)

SIS_ES.TXT

- 40 columns by 3018 rows of 8-Digit ASCII data
- E_s (uW/cm^2/nm):

Col 01 = Julian Day (GMT, 2000)
Col 02 = Time (GMT fractional hour)
Col 03 = Es (370.15 nm)
•
•
•
Col 40 = Es (724.70 nm)

SIS_PAR.TXT

- 3 columns by 3018 rows of 8-Digit ASCII data
- PAR (uMoles/m^2/s), calculated from E_s (uW/cm^2/nm):

Col 01 = Julian Day (GMT, 1999)
Col 02 = Time (GMT fractional hour)
Col 03 = PAR (uMoles/m^2/s)

Table 2: Summary of MOS and SIS data file formats.

SPMR and SMSR. Satlantic Profiling Mutli-Channel Radiometer (SPMR), with accompanying surface reference (SMSR), casts were conducted at least four times per day. The purpose of using this radiometer was to make comparisons with other optical instruments taking similar measurements, as part of the calibration validation and refinement efforts of current bio-optical algorithms for different water masses. The SPMR, model OCP-1000, has seven optical channels in both the downwelling irradiance and upwelling radiance sensors, as well as in the surface irradiance sensor. The filters used were designed to match the 10 nm bandwidths required by the SeaWiFS calibration/validation protocols (SPMR User's Manual, 1996). The center wavelengths for the seven bands were 411, 443, 490, 519, 555, 665 and 683 nm. All three sensors sample at 6 Hz and have proven to be relatively stable.

Two profiles were made after the CTD cast and before the MOS deployment, followed by two casts after MOS. The SMSR was secured to the ship about 10 m above the sea surface. The profiler was lowered into the water by hand from the back deck of the ship and allowed to drift away. A preliminary 50 m cast was always done to allow for temperature equilibration of the optical sensors as well as a depth tare for the pressure transducer. The back deck of the ship always faced the sun to minimize the effects of the ship contaminating the ambient light field. A stable free-fall (good velocity and low tilt) was usually achieved in the top two meters by attaching a 2 kg ballast weight to the profiler.

SPMR and SMSR data were collected and processed by the standard software packages provided by Satlantic Inc., Proview and Prosoft, respectively. In the course of evaluating the computational procedures provided in their software, several problems were identified, and the most serious of those are discussed in the following paragraphs. Those variables which have been identified as having problems should be recalculated with correct procedures following Gordon (1988).

Satlantic Inc. provides a standard software package for both data acquisition and processing. Proview creates raw binary files which Prosoft reads for subsequent processing as outlined in the NASA Technical Memorandum Vol. 25. During level 2 processing, calibration files are used to remove the dark offset and raw counts are converted into physical units. Level 2 profiler files have the *.pro extension and reference files have the *.ref extension.

Files with a *.bin extension are SPMR level 3 data. The file consists of merged profiler (SPMR) and reference (SMSR) data binned to 1 m bins. The last step in level 3 depth shifts the binned radiance data to match the irradiance binned data. The calculations of the attenuation coefficient for both subsurface radiance and irradiance are made using the 1 m binned data, and written to files with the *.k extension. These calculations should be made before the binning process to reduce the level of uncertainty. Solar normalized water leaving radiances are then calculated using data from both of these files, and written to files with the *.lwn extension.

During the MOCE-7 cruise, SPMR and SMSR data were collected by a slightly different method than assumed by the Prosoft.40f processing programs. The Proview data acquisition program refers to this as a "dry" calibration method and must be taken into account during the calibration phase in level 2 processing. $E_s(0+)$ is the variable directly measured when the SMSR is "dry" by averaging all of the reference data taken during the cast. In the "wet" case for the SMSR, it is fixed to a float 0.3 m below the sea surface sampling near the profiler. In this case $E_s(z0)$ is directly measured in averaging all of the reference data collected during the cast. $E_s(0-)$ is calculated by projection of $E_s(z0)$ to just below the sea surface. This calculation uses the surface-most attenuation coefficient for irradiance measured by the profiler. $E_s(0+)$ is then calculated by propagating $E_s(0-)$ through the sea surface.

The LWN.M Prosoft 4.0f module calculates these products. Unfortunately this function does not account for the "dry" reference case and assumes the reference is always "wet". Calculations of $E_s(z0)$ and $E_s(0-)$ are not necessary and the calculation of $E_s(0+)$ is incorrect and results in an increase in $E_s(0+)$ by 4-5 % under clear sky conditions. Therefore, data columns 4-6 are incorrect and should be ignored in the *.lwn files.

The calculation of solar normalized water leaving radiance is also questionable. The function uses equation (63) from the NASA Technical Memorandum Vol. 25. It appears that both the cosine correction and mean earth-sun distance correction are not implemented as in equation (60) of the same memorandum. The band weighted values for mean extraterrestrial irradiance, F_o, remain constant regardless of time of day or day of the year. LWN.M solar normalizes water leaving radiances by multiplying $L_u(0+)$ by the ratio $F_o/E_s(0+)$. Not only is this equation questionable, it also uses incorrect values for $E_s(0+)$ described above. Therefore columns 2 and 11 in these files are also incorrect. The only data which should be regarded as valid are columns 1, 3, and 7-10 in the *.lwn files.

Upwelling Radiance Distributions. During MOCE-7, the upwelling radiance distribution from just below the surface was obtained at four wavelengths for each station. The radiance distribution is defined as the radiant flux per unit solid angle per unit projected area from a given direction (Morel & Smith, 1982). When combined with spectral filtering, a profile of the radiance distribution provides the most complete set of data on the ambient underwater light field. Other measures of the underwater light field such as the downwelling and upwelling irradiances, E_d and E_u, and the scalar irradiance, E_o, can be obtained from the measurement of the radiance distribution with simple integrations (Jerlov, 1976).

The Radiance Distribution Camera System (RDCS) used during this cruise was described fully in Voss *et al.*(1992). The central feature of this system was the use of cooled CCD arrays (First Magnitude, Starscape II) to collect the radiance information. These cameras were 480 x 542 arrays and were cooled to approximately -30°C. The cooling reduced the dark noise significantly thus increasing the allowable integration times. The camera images were digitized by a 16 bit frame grabber thus significantly increasing the intrascene dynamic range. The light collected by the fisheye lens was transmitted through spectral and neutral density filters before being imaged on the surface of the array. There were four channels each of spectral and neutral density filters which allowed four different spectral wavelengths to be investigated.

Inside the underwater housing, a single board 386Sx, 16 MHz computer (Diversified Technology, CAT 970) controlled the camera and frame grabber. A 100 MByte hard drive was also enclosed in the underwater housing. Since the computer controlling the camera and the storage device are contained in the housing, data communication to the surface was greatly reduced. Only subsampled low resolution images were needed at the surface to check data quality and set exposure times. Data communication between the surface and the underwater unit was performed using a serial 9600 baud transmission and standard software. This allowed the surface computer to display the complete operations of the underwater computer without complicated additional software.

Integrated in the system were standard irradiance collectors for upwelling and downwelling irradiance. These collectors (Biospherical Instruments, MER-2040) allowed the calibration of the cameras to be checked, as the integrated radiance distribution can be compared with the irradiance data. Thus calibration drift can be monitored. While the camera was limited to four channels of radiance distribution data, upwelling and downwelling irradiance were collected at eight different wavelengths to better monitor the spectral distribution of the underwater light field.

Pitch and roll indicators (Accustar) were provided along with a flux gate compass. These allowed the instrument orientation to be determined, and the images mapped to a precise coordinate system. The irradiance information, pitch and roll, and heading were combined with depth and water temperature and stored when images were taken.

Because of the volume of data included in each image, the data were saved in binary format. Each data image was 528 x 528, and the data were stored as single precision floating point numbers (4 bytes/data point) with big-endian byte ordering. There is a 142 byte header that must be skipped in each file. Data are in units of uW/cm^2/nm/sr.

FOS. Accurate spectroradiometric measurement systems of apparent optical properties within the marine environment over a large spectral range must have large dynamic ranges and stray light rejections on the order of 10^{12} and 10^{-8}, respectively. Measurements in spectral regions where attenuation is dominated by absorption processes (i.e. the near-infrared due to water absorption), must also take into consideration the effects of instrument self-shading (Gordon and Ding, 1992).

A prototype of a Fiber Optic Spectrometer (FOS) system was developed in order to study the uncertainties associated with instrument self-shading in high absorption cases. During MOCE-7, the FOS system incorporated two modified American Holographic AH4000 series dual beam spectrometers (visible, f5 and near-infrared, f3.5) housed in a cylindrical, 11.5 x 48.5 cm, pressure case. These American Holographic dual beam spectrographs were designed to allow simultaneous dispersion of the irradiance and radiance spectra onto a 512-element Hamamatsu, self-scanning diode array. This system measured the incident surface irradiance, downwelled irradiance, and upwelled radiance at nominal spectral resolutions of 5 nm from 375 to 725 nm and 10 nm from 600 to 1100 nm. The spectrometers were coupled to radiance and irradiance collectors with 1.0 mm and 0.10 mm silica/silica glass fibers, respectively. The radiance collector fibers were displaced 0.5 to 1.5 m from the instrument housing, via a dual optical pressure housing feedthrough, to further reduce shading effects. Incident surface irradiance was acquired only during the near-surface radiance measurements. Preliminary results for data collected in clear and turbid waters showed that instrument self-shading also contributed major uncertainties in apparent optical properaties within turbid/eutrophic waters.

Phytoplankton and CDOM Absorption. Vertical profiling water samples were obtained from 17-liter CTD rosette sampling bottles, and alongtrack and station subsurface water samples were collected from the ship's uncontaminated seawater system.

For phytoplankton absorption (A_{ph}) data, one to eight liter aliquots of seawater were vacuum filtered through 47 mm Whatman GF/F filters. The filters were placed into individual petri dishes and refrigerated until spectrophotometric analysis, which occurred within 24 hours of sample collection. The filter samples were analyzed for particulate (A_p) and detrital (A_d) absorption according to the method outlined by Kishino, *et. al.* (1985) and to SeaWiFS protocols (Mueller and Austin, 1992). Spectral absorption was measured from 400-750 nm at 2 nm intervals. Spectral scans of wet, clean GF/F filters were used as blanks.

Spectral analysis was performed on a Hewlett-Packard Diode Array Spectrophotometer (HP8452A) with an integrating sphere (RSA-HP-84) from Labsphere, and the spectrophotometric data acquisition computer was a Toshiba T3200. Prior to spectrographic analysis, the spectrophotometer and the integrating sphere lamps were turned on and warmed up for a minimum of 45 minutes. Stable air blanks were considered indicative of a sufficiently warmed up spectrographic setup. A_{ph} values were transformed natural log and final A_{ph} values were calculated using beta correction (Mitchell and Kiefer, 1984) regression coefficients determined prior to the cruise.

The CDOM water samples were analyzed according to SeaWiFS protocols (Mueller and Austin, 1992). Aliquots of seawater were filtered with a 0.2 um in-line Gelman Sterivex filter. Spectral absorption was measured in a 10 cm cuvette from 400-750 nm at 2 nm intervals. Spectral scans of fresh nanopure water, filtered in the same manner as the seawater aliquots, were used as blanks. Spectral analysis was performed on the HP8452A and the Toshiba T3200. Final CDOM values were converted from log base 10 to log base e.

Biological Data Sets

Pigment concentrations and particle size distribution were the two types of biological data sets collected during MOCE-7.

Pigment Concentrations. Chlorophyll *a* concentrations were determined using two different techniques - fluorometric analysis and high performance liquid chromatography (HPLC). Fluorometric pigment samples were collected on Gelman 25 mm GF/F glass fiber filters and stored in liquid nitrogen. The filters were then extracted in 10 mls of 90% acetone for 24 hours and sonicated with a microprobe system to enhance extraction efficiencies. Samples were then centrifuged and measured on the ship using the standard fluorometric method of Holm-Hansen *et al.* (1965). Chlorophyll and phaeopigment concentrations were then calculated.

HPLC samples were collected on Gelman 25 mm GF/F glass fiber filters and stored in liquid N2. The filters were then extracted in 4 mls of 90% acetone for 24 hours and then sonicated with a microprobe system to enhance extraction efficiencies. Samples were then centrifuged and filtered using in-line 0.2 micrometer PTFE filters. An internal pigment standard (canthaxanthin, which is not normally found in samples) was added to the 90% acetone to correct for volume changes during the solvent extraction process. Since canthaxanthin is a carotenoid and does not fluoresce, it does not affect the fluorometric analysis (see below).

The HPLC method used was that proposed by Wright *et al.* (1991). Pigments were separated on the ODS-2 C18 column using a three solvent gradient system at a flow rate of 1 ml min^{-1}. The separation of the various pigments required about 30 min with the pigment peaks being detected by two absorption detectors: a UV2000 two channel detector measuring absorption at 436 and 450 nm and a UV6000 scanning diode array detector measuring at 1 nm resolution from 400 to 700 nm. In addition, a fluorescence detector (Ex: 404 nm, Em: 680 nm) was used to detect and quantify the various chlorophyll degradation products, which usually occur at low concentrations. Since 436 and 450 nm were measured simultaneously for the monovinyl chlorophyll a and divinyl chlorophyll a peak, and each compound absorbs differently at these two wavelengths, it is possible to correct for the divinyl chlorophyll *a* contamination by monitoring changes in this ratio as a function as the divinyl percentage changes

(Latasa *et al.*, 1996). Accuracy for each pigment compound was based on availability of pigment standards and the selection of pigment specific extinction coefficients.

A 100 microliter aliquot of the HPLC samples was diluted in 8 mls of 90% acetone and measured using the standard fluorometric method of Holm-Hansen *et al.* (1965).

Particle Size Distribution. A Spectrex laser particle counter was used to collect the particle size distribution data during MOCE-7. This instrument uses as its basic light source an HeNe laser diode (wavelength 670.8 nm). The beam from this laser is spatially filtered and focused by a lens assembly to form a well-defined illuminated volume within the liquid being analyzed. The laser moves rapidly to provide the necessary scattering. This accounts for the sensitivity of the counter and permits measurement of particles down to 1 um. The optical collection system which is part of the photodetector assembly is designed to provide a definite depth-of-focus. This zone is approximately 3.5 cm from the black target and lens assembly. The walls of a typical bottle placed on the stage are outside this zone and, therefore, out of focus.

This particle counting method is based on two assumptions. The first is that the particle population is low, so that the way a particle in the path of the laser beam scatters the incident light is independent of the surrounding particles. This means that only one particle at a time is sending a signal to the counter. Low concentration also keeps coincident counts to a minimum. The second assumption is that the particles are large enough (greater than five times the wavelength of the light) so that true reflection of light is occurring. This means that light reflected is proportional to the surface of the particle or the size of the particle.

In operation, a focused laser beam is directed through the sample liquid. Particles are detected when they pass through the laser in the focus area. Light is scattered from the particle and a photodiode detects that portion of the light reflected in a near forward direction over a solid angle ranging from 4° - 19° from the light path. A detection unit analyzes the light pulse generated by the particle and any abnormal pulse is rejected. An abnormal pulse can be caused by a particle out of the focus area of the laser or a particle in the focus area but not completely through the laser beam. Particles grazed by the laser reflect less light than the size of the particle would indicate, and the pulse of the light is shorter than if the particle were hit completely by the laser beam. Short pulse duration is the determining factor for the rejection of pulses caused by a particle grazing the light beam. Particles outside the focus area of the laser cause a diffused flash on the photocell and so the detection unit rejects these diffused pulses.

When the laser particle counter analyzes a sample, two processes occur simultaneously:

1) An electronic counter counts the number of times a new particle signal is detected. The counter has the total number of particles that were scanned by the laser beam during the fixed counter cycle. Since the counter works independently of the computer and is fast, it counts all of the particles that are scanned during its active interval.

2) The computer captures some of the signals seen by the counting circuit and analyzes each to determine particle size. Since the computer requires time to analyze any given signal, several subsequent particle signals may go unnoticed while it is analyzing the first particle's signal. The net effect of this is that the computer only sizes some of the particles. So the computer only gets relative proportions of the sizes occurring in the sample since it missed some of the particles.

This second process is the sizing component of the sample analysis. These measurements are based upon a brief illumination of each individual particle by the laser beam. The size of each particle is determined by the light scattered by the particle and the fraction of that light which reaches the photo-detector.

Prior to any measurements, the laser particle counter was calibrated using the manufacturer's procedures and calibration standards. These standards are sealed 200 ml bottles of alcohol and freon proportioned to each other to match the specific gravity of polystyrene spheres. The liquid has been filtered through a 0.2 _m filter. There are two types of standards. Standards that contain a precisely known number of specific sized spheres and an ultra-clean, particle free standard to establish accurate background levels. This calibration is designed especially for the counting aspect of the sampling process.

A second calibration procedure was conducted in order to establish accurate representation of particle sizing in samples. A calibration sample was made using RO water and at least two sizes of Coulter microsphere latex beads. This sample had an unknown particle count but has a definitive dual spike in the size distribution.

Vertical profile water samples were collected by ten 17-liter custom-made water samplers attached to a Sea-Bird CTD Carousel. Water samples were obtained on the up-cast at inflection points and other significant depths in the water column based on observations during the down cast. Samples were then drawn from these bottles into 200 ml containers for transfer to the laser counter in the wet lab. Alongtrack surface water samples were taken in coordination with other investigators during 2-dimensional grid profiling operations that lasted approximately six hours apiece. During these grids as many as 30 water samples at 10 minute intervals were taken. The samples were supplied by the ship's uncontaminated seachest, from approximately 3 m in depth. Samples were drawn into 200 ml containers directly from the pump hose.

In accordance with the manufacturer's suggested measurement procedure, particle samples were 100 ml in volume. The samples were placed in a clean 150 ml glass beaker and placed in the counter to be analyzed. The sample was stirred via magnetic stir-bar to prevent particle settling during analysis. Due to the ability of the Spectrex PC-2000 to analyze samples with low particle concentration, no filtration was necessary to increase the concentration of the samples.

Physical Data Sets

Temperature and salinity data were collected by two instrumentation packages during MOCE-7. Vertical profiles were obtained with a SeaBird conductivity, temperature, depth profiler (CTD) and alongtrack data were collected with a Falmouth thermosalinograph (TSG). Total suspended material (TSM), particulate organic carbon (POC), and particulate organic nitrogen (PON) data were collected from the CTD water sampling rosette as well as from the ship's uncontaminated seawater system.

CTD. The purpose of collecting this data set was to obtain *in situ* ocean data characterizing the upper ocean bio-optical properties. The purposes of these data were twofold: provide surface truth for ocean color satellites and develop bio-optical algorithms relating water-leaving radiance to dissolved and suspended particulate material concentrations in surface waters.

Data were obtained using a Sea-Bird SBE911plus CTD profiler. Values of electrical conductivity, temperature, pressure, dissolved oxygen, beam attenuation at 660 nm, chlorophyll *a* fluorescence at 680 nm and 670 nm were obtained at 24 Hz. The CTD descent speed was 30 m/min. Details of the shipboard procedures are in Broenkow *et al.* (1994) and some details of the Sea-Bird CTD data processing procedure are in Broenkow *et al.* (1995). With the exception of beam attenuation and fluorescence, Sea-Bird (1994) data processing procedures were followed.

Two classes of data were collected. Vertical CTD profiles of water column properties and water analyses for particulate materials. In addition to making particulate analyses from CTD rosette bottles, samples were also taken from the ship's seachest during alongtrack horizontal profiles and while on station.

Water samples were collected by 10 custom-made 17-liter water samplers attached to the Sea-Bird Carousel. Water samples were obtained on the upcast at inflection points or other significant depths in the water column based on observation during the down cast. The primary purpose of the water samples was to obtain large volume samples for analyses of TSM, phytoplankton pigment analyses by HPLC, POC and PON, particle size analyses (NOAA/NESDIS), and calibration samples for the CTD.

Alongtrack water samples were taken in coordination with other investigators during tracks between stations and from high to low fluorescence. Water samples were provided by the ship's seachest with an intake at 3 m. Additionally water samples were collected from the ship's seachest and by bucket during each station. The purpose was to determine the variability of TSM/POC/PON and pigments during the station.

Near local apparent noon, Secchi depth measurements were made with a 30 cm, all white Secchi disk, carefully avoiding surface glint. The depth estimates were made both by lowering the disk until it faded from view and raising it again until it returned to view. The reported Secchi depths are the mean of the two readings. Ocean color as sensed by the human eye was estimated by Munsell color chips (Munsell Color Company, Baltimore Md.) selected by R.W. Austin (Scripps Visibility Laboratory). Two or more observers compared the color of the Secchi disk suspended at half its disappearance depth.

Total suspended particulates were determined by filtering 0.5 to 9 liters of water through 47 mm diameter, 0.45 um pore-size Millepore HP/EP mixed-ester cellulose filters. These filters were desiccated and tared to a constant (~20 ug) weight and stored in separate Petri dishes. Water was vacuum filtered aboard ship using a pressure differential of 0.5 to 0.7 atmospheres. Sea salts were removed by two 10 ml rinses of deionized (Mille-Q) water. These filters have a 6 mm hydrophobic edge which eliminates the need to rinse sea salts from the filter rim. After sample collection the filters were returned to the Petri dish, dried at 60°C, and stored until analysis ashore. Suspended sediment weights were determined by weighing each filter on a Mettler H54-AR balance. Weighing was repeated three times or more until the difference between weights was less than 40 ug.

Separate samples were filtered for particulate organic carbon and nitrogen analyses. Approximately 1 to 4 liters of water were pressure filtered through 25 mm Whatman glass fiber GF/F filters having a nominal pore size of 0.7 um. These filters were pretreated by ashing in a muffle furnace at 500°C for two hours. Each filter was stored in an ashed aluminum-lined Petri dish. Following filtration, the filters were returned to the Petri dish, folded, gently creased, dried at 60°C, and stored until analysis ashore. Organic carbon and nitrogen were determined by combustion analysis with a Leeman Labs Model 440 Element Analyzer. Acetanilide standards were analyzed every 15th sample, and the maximum deviation of these standards never exceeded the 5% limits, which is the accepted precision of the method (University of Maryland, 1992). The limits of detection are 1 ug C mg^{-1} sample for carbon and 0.1 ug N mg^{-1} for nitrogen.

SeaBird CTD/Carousel data were collected using SeaBird software on a DOS laptop computer. Data acquisition and processing procedures are explained in detail by Feinholz and Broenkow (1994) and processing steps are illustrated in a tutorial (Broenkow *et al.*, 1994). Data from all instruments were kept in an MLML_DBASE format which can be displayed, edited and processed with a single suite of programs (Broenkow and Reaves, 1994). CTD data files were named by instrument (SBE) and the a sequential file number.

Field check samples for dissolved oxygen were taken during each cast. These samples were taken at interesting depths conforming to the requirements for characterizing the near-surface photic zone of most interest to the MODIS program. Deeper samples were collected to provide calibration data points through the oxygen minimum. Because of the known difficulty in using membrane oxygen electrodes, considerable work was involved in making field calibration measurements. The reality of electrode oxygen measurements accuracy is relatively poor. Each oxygen electrode has a finite life of a few hundred hours of use, and the sensor degrades throughout its lifetime such that calibrations must be done on a cruise-by-cruise (or cast-by-cast) basis.

The modified Marek transmissometer used on previous MOCE cruises was replaced with a 25 cm 660 nm C-Star transmissometer. Air calibrations were performed prior to each CTD cast by noting the voltage when the transmissometer was clean and dry. Beam attenuation was calculated using a modification to Wet Lab equations. Wet Lab calculates beam attenuation as

$$c = -1/x\ (\ln(V_{sig} - V_d) / (V_{ref} - V_d))$$

where x is the path length (0.25 m), V_{sig} is the transmissometer voltage, V_d is the voltage with the path blocked (0.055) and V_{ref} is the voltage with clean water in the path (4.753). Note that air calibrations are not included in the equation. If there are trends in the air calibrations, V_{ref} must be adjusted. The corrected reference voltage, V_{refcor}, is calculated as

$$V_{refcor} = V_{ref} /[V_{air} / \mathrm{AirCal}]$$

where V_{air} was the C-star calibrated air calibration (4.835) and AirCal was the air calibration taken before each cast. This corrected reference voltage (V_{refcor}) was then used in the Wet Lab equation above.

<u>TSG</u>. MOCE-7 TSG data were collected with a Falmouth thermosalinograph, which was placed in-line of the uncontaminated shipboard seachest. This seawater was pumped from a depth of

approximately 3 m. Seawater was flushed into a 2 liter flush housing containing the conductivity and temperature probes. Thermosalinograph data were collected continuously throughout the cruise.

Meteorological Data Sets

Four types of meteorological data sets were collected during MOCE-7: atmospheric aerosol optical thickness, sky condition imagery, barometric pressure, and relative humidity.

Aerosol Optical Thickness. Data were collected with two types of instrumentation systems: a Hand-Held Contrast Reduction Meter (HHCRM) and hand-held multi-band sun photometers (MICROTOPS II). The sun photometers were used to measure intensity of direct sunlight, water vapor column, and ozone column. In order to derive spectral transmittances, HHCRM measurements bracketed the overpasses. Water vapor column, ozone column, and intensity of direct sunlight were measured during each overpass using MICROTOPS II.

The HHCRM sun photometer instrumentation specifications were in agreement with the WMO sun photometer specifications. Specifically, the instrument had a 2 degree FOV, temperature stabilization, and a precision of +/- 0.01%. The HHCRM wavelengths corresponded to 380, 400, 410, 440, 520, 560, 590, 610, 670, and 780 nm.

Two MICROTOPS II sun photometers (#4077 and #4079) measured the intensity of direct sunlight. These instruments were equipped with five optical collimators, with a full field of view of 2.5 degrees, and internal baffles eliminating internal reflections. Each channel was fitted with a narrow-band interference filter and a photodiode suitable for the particular wavelength range. The specific channel wavelengths were 340, 380, 440, 500, and 675 nm. When the image of the sun is centered at the cross-hairs of the sun target, then all channels are looking directly at the solar disk. The radiation captured by the collimators were then filtered through bandpass filters and passed into the photodiodes, which produced an electrical current proportional to the radiant power intercepted by the photodiodes. These signals were amplified and converted to digital form in an A/D converter.

Two other MICROTOPS II sun photometers (#3691 and #4060) were used to measure the total ozone column, water vapor column, and intensity of direct sunlight at 1020 nm. Ozone strongly absorbs shorter wavelengths of UV radiation rather than the longer wavelengths. MICROTOPS II uses that relationship to derive the total ozone column (the equivalent thickness of pure ozone layer at standard pressure and temperature) from measurements of three wavelengths in the UV region (305, 312, and 320 nm). The precipitable water column was determined based on measurements at 936 nm (water absorption peak) and 1020 nm (no absorption by water). The aerosol optical thickness at 1020 nm was calculated based on the extraterrestrial radiation at that wavelength, corrected for the sun-earth distance, and the ground level measurement of the radiation at 1020 nm.

Multiple measurements of the solar beam were obtained during stable atmospheric conditions, then the Langley method was used to obtain the atmospheric transmittances. This method consists of plotting the natural logarithm of the voltage from the sun photometer versus the inverse of the cosine of the solar angle. The slope of this straight line was the total optical depth of one atmosphere. If only a single measurement was obtained, the instrument calibration was applied to determine radiance, which can be combined with the extraterrestrial solar irradiance to calculate the atmospheric optical depth. To obtain the aerosol optical depth, total optical depth was used with computed optical depth due to molecular scattering (Rayleigh optical depth), and absorption by ozone. By subtracting the ozone optical depths from the total measurements, the aerosol optical depth was determined.

Sky Condition Imagery. The Sky-Cam system consisted of off-the-shelf components integrated to produce wide angle time lapse motion studies of clear sky/cloud cover conditions during daylight hours for the entire cruise. The individual units consisted of a Pulnix 2/3 CCD video camera head (TMC-74), producing NTSC composite video at 330(H) x 500 (V) lines of resolution. The minimum illumination was 5 lux at F=1.4. It was coupled with a Computar fish-eye lens (M3818) with a published horizonal angle of view of 138°. The camera and lens were housed in a modified underwater housing fitted with a hemispherical sphere front lens which further increased the field of view. The assembly was mounted looking straight up, in the highest accessible position on the ship.

The camera was cabled to a Sony Digital Surveillance Recorder (HSR-1/1P). The recorder consisted of a 4.3 GB disk drive with DV cassette tapes (DVM or PDVM series) providing the storage medium. The recorder provided a horizonal resolution of more than 500 TV lines. Depending upon tape size and resolution selected, a storage capacity of more than 60 GB was possible. Each recorded frame was documented with the date (M/D/Y) and time (GMT).

Barometric Pressure and Relative Humidity. Barometer data were acquired using a Setra 470 Digital Pressure Transducer. The transducer was mounted approximately 8 m above the sea surface, and barometer data were collected continuously throughout the cruise. Data files were usually 2-4K in size, and each data file was a 10 minute average of the 1 Hz hourly files.

Relative humidity (%RH) and air temperature (T_{air}) data were acquired with a Vaisala HMD 30YB humidity and temperature transmitter. The transmitter was mounted approximately 8 meters above the sea surface, and data were collected continuously throughout the cruise. These data files were usually 4K in size. Each data file was a 10 minute average of the 1 Hz hourly files.

Appendix 2: Calibrations and maintenance schedules for MLML standards and instruments

- SLM

04-Jan-2001 Pos-MOCE7 : GS5000-F453 before & after SIS101 & MOS202
05-Jan-2001 Pos-MOCE7 : OL420-S3W5D100 after MOS202cfg08 Lu
10-Jan-2001 Pos-MOCE7 : OL425-S3W*D100 after MOS202cfg08 Lu
12-Jan-2001 Pos-MOCE7 : OL420-S3W6D40 after MOBY214 LuB,M,T
17-Jan-2001 Pos-MOCE7 : GS5000-F453 after MOBY214 EdB,M,T,S
24-Jan-2001 Pos-MOCE7 : OL420-S3W5D100 after MOS204cfg04
24-Jan-2001 Pre-MOCE8 : via GS5000-F453 after FOS/Yarbrough
25-Jan-2001 Pre-MOCE8 : OL420-S3W5D40 after FOS/Yarbrough
09-Feb-2001 Pre-MOCE8 : OL425-S3W6D100 after MOS204cfg05
17-Feb-2001 Pre-MOCE8 : OL425-S3W6D100 after MD5/Koval
20-Feb-2001 Pre-MOCE8 : OL425-S3W6D100 after MOBY216 LuB,M,T
21-Feb-2001 Pre-MOCE8 : GS5000-F453 after MOBY216 EdB,M,T,S
23-Feb-2001 Pre-MOCE8 : GS5000-F453 after MOBY216 EdB,M,T,S
24-Feb-2001 Pre-MOCE8 : OL425-S3W6D100 after MOBY216 LuB,M,T
13-Mar-2001 NIST 2001#1 : NPR-1234Lamps with EOS VXR
13-Mar-2001 NIST 2001#1 : NPR-#4Lamp with EOS VXR & SIMBIOS SXRII
14-Mar-2001 NIST 2001#1 : OL420-S3W5/6D100 with EOS VXR & SIMBIOS SXRII
14-Mar-2001 NIST 2001#1 : OL425-S3W5/6D100 with EOS VXR & SIMBIOS SXRII
14-Mar-2001 NIST 2001#1 : OL425-S3W5/6D100 with EOS VXR & SIMBIOS SXRII
14-Mar-2001 NIST 2001#1 : OL420-S3W5/6D100 with EOS VXR & SIMBIOS SXRII
17-Mar-2001 NIST 2001#1 : NPR-#4Lamp with EOS VXR & SIMBIOS SXRII
03-Apr-2001 Pos-MOCE8 : OL425-S3W6D100 after MOBY215 LuB,M,T
04-Apr-2001 Pos-MOCE8 : GS5000-F453 after MOBY215 EdB,M,T,S
17-Apr-2001 Pos-MOCE8 : GS5000-F453 before&after MOS202cfg08 Ed
17-Apr-2001 Pos-MOCE8 : OL425-S3W6D100 after MOS202cfg08 Lu
24-May-2001 Pos-MOCE8 : OL425-S3W6D100 after MOS205cfg05 Lu
25-May-2001 Pos-MOCE8 : OL420-S3W5D100 after MOS205cfg05 Lu
26-May-2001 Pre-L69 : OL425-S3W6D100 after MOS205cfg06 Lu
29-May-2001 Pre-L69 : OL425-S3W6D100 after MOBY217 LuB,M,T
30-May-2001 Pre-L69 : GS5000-F454 after MOBY215 Eu,EdB,M,T,S

- SIS101

04-Jan-2001 Pos-MOCE7 : SIS101cfg04 Es via GS5000-F453
17-Apr-2001 Pos-MOCE8 : SIS101cfg04 Es via GS5000-F453

Appendix 2: (Continued)

- MOS202

04-Jan-2001 Pos-MOCE7 : MOS202cfg08 Ed via GS5000-F453
05-Jan-2001 Pos-MOCE7 : MOS202cfg08 Lu via OL420-S3W5D100
06-Jan-2001 Pos-MOCE7 : MOS202cfg08 Lu Wave via HgA, Ne
10-Jan-2001 Pos-MOCE7 : MOS202cfg08 Lu & Int via OL425-S3W*D100
15-Mar-2001 NIST 2001#1 : MOS202cfg08 Lu via NIST HeNe & Ar lasers
16-Mar-2001 NIST 2001#1 : MOS202cfg08 Ed via NIST HeNe & Ar lasers
16-Mar-2001 NIST 2001#1 : MOS202cfg08 Ed via NIST tunable diode laser
17-Mar-2001 NIST 2001#1 : MOS202cfg08 Lu via NIST tunable diode laser
17-Apr-2001 Pos-MOCE8 : MOS202cfg08 Ed via GS5000-F453
17-Apr-2001 Pos-MOCE8 : MOS202cfg08 Lu via OL425-S3W6D100
17-Apr-2001 Pos-MOCE8 : MOS202cfg08 Lu Wave via HgA, Ne
25-Apr-2001 NIST 2001#2 : MOS202cfg08 Lu via HgA, OL420 +/- BG28
26-Apr-2001 NIST 2001#2 : OL420 +/- BG28, BG39, PER
27-Apr-2001 NIST 2001#2 : OL420 +/- BG28, BG39, PER
27-Apr-2001 NIST 2001#2 : s1, SIRCUS Coumarin 540 dye 520:573nm
28-Apr-2001 NIST 2001#2 : s2, SIRCUS Coumarin 540 dye 520:565nm / 555:565 @ 0.2nm
29-Apr-2001 NIST 2001#2 : s3, SIRCUS DCM dye 615:695nm
29-Apr-2001 NIST 2001#2 : s4, SIRCUS Ti Saphire 732:832nm
29-Apr-2001 NIST 2001#2 : s5, SIRCUS Ti Saphire 761:770nm @ 0.2nm
30-Apr-2001 NIST 2001#2 : s6, SIRCUS Ti Saphire 761:830nm
30-Apr-2001 NIST 2001#2 : s7, SIRCUS Ti Saphire 695:731nm
30-Apr-2001 NIST 2001#2 : s8, SIRCUS Ti Saphire 825:906nm
30-Apr-2001 NIST 2001#2 : s9, SIRCUS Ti Saphire 860:865nm @ 0.2nm
30-Apr-2001 NIST 2001#2 : s10, SIRCUS Ti Saphire 901:936nm
01-May-2001 NIST 2001#2 : s11, SIRCUS 540 Dye 512:562nm / 558:561 @ 0.2nm
01-May-2001 NIST 2001#2 : s12, SIRCUS Coumarin 480 Dye 472:512nm
01-May-2001 NIST 2001#2 : s13, SIRCUS Stilbene 435:475nm
02-May-2001 NIST 2001#2 : s14, SIRCUS Stilbene 415:440nm / 430:440 @ 0.2 nm
02-May-2001 NIST 2001#2 : s15, SIRCUS R66 Dye 570:615nm
02-May-2001 NIST 2001#2 : s16, SIRCUS R66 Dye 570:615nm
03-May-2001 NIST 2001#2 : s17, SIRCUS DCM Dye 629 & 675nm TT7 Temperature
04-May-2001 NIST 2001#2 : s18, SIRCUS direct laser 515nm TT7 Temperature
07-May-2001 NIST 2001#2 : s19, SIRCUS doubled Ti Saphire 385:411nm

07-May-2001 NIST 2001#2 : s20, SIRCUS doubled Ti Saphire 362:380nm
09-May-2001 NIST 2001#2 : s21, SIRCUS Ti Saphire 722:830nm via DOWN Ed
09-May-2001 NIST 2001#2 : s22, SIRCUS Argon Ion 454:515nm via DOWN Ed

- MOS204

24-Jan-2001 Pos-MOCE7 : MOS204cfg04 Lu via OL420-S3W5D100 << Pos-MOBY214 >>
09-Feb-2001 Pre-MOCE8 : MOS204cfg05 Lu & Int via OL425-S3W*D100 << Pre-MOBY216
09-Feb-2001 Pre-MOCE8 : MOS204cfg05 Wave via HgA, Ne Lu

Appendix 2: (Continued)

- MOS205

18-Mar-2001 NIST 2001#1 : MOS205cfg05 Lu via NIST Ar Laser
24-May-2001 Pos-MOCE8 : MOS205cfg05 Lu via OL425-S3W6D100 << Post-MOBY215 >>
24-May-2001 Pos-MOCE8 : MOS205cfg05 Lu via HgA & Ne
25-May-2001 Pos-MOCE8 : MOS205cfg05 Lu via OL420-S3W5D100 - broke LEDs !
26-May-2001 Pre-L69 : MOS205cfg06 Lu via OL425-S3W6D100 << Pre-MOBY217 >>
26-May-2001 Pre-L69 : MOS205cfg06 Lu via HgA & Ne

- MOBY214

12-Jan-2001 Pos-MOCE7 : LuB,M,T via OL420-S3W6D40
17-Jan-2001 Pos-MOCE7 : EdB,M,T,S via GS5000-F453

- MOBY215

18-Mar-2001 NIST 2001#1 : LuMid & LuMOS + Spectralon sphere via NIST Ar laser
03-Apr-2001 Pos-MOCE8 : LuB,M,T via OL425-S3W6D100
04-Apr-2001 Pos-MOCE8 : EdB,M,T,S via GS5000-F453

- MOBY216

20-Feb-2001 Pre-MOCE8 : LuB,M,T via OL425-S3W6D100
21-Feb-2001 Pre-MOCE8 : EdB,M,T,S via GS5000-F453
23-Feb-2001 Pre-MOCE8 : EdB,M,T,S via GS5000-F453
24-Feb-2001 Pre-MOCE8 : LuB,M,T via OL425-S3W6D100

- MOBY217

29-May-2001 Pre-L69 : LuB,M,T via OL425-S3W6D100
29-May-2001 Pre-L69 : EuMOS, EdB,M,T,S via GS5000-F454

Stray Light Characterizations for MOBY

Steve Brown, Keith Lykke, and Carol Johnson

NIST

Mike Feinholz, Mark Yarbrough, and Stephanie Flora

Moss Landing Marine Laboratories

Dennis Clark

NOAA/NESDIS

2001 Ocean Color Research Team Meeting

San Diego, California

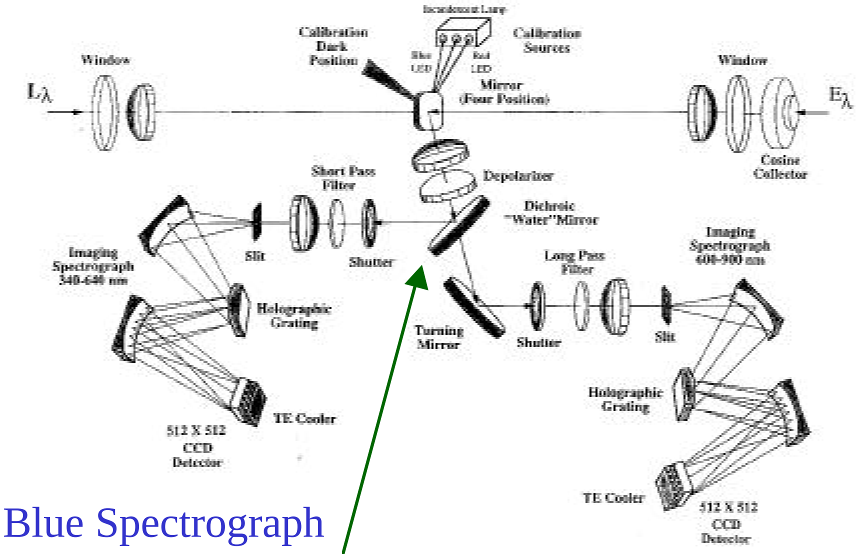
May 21 to 24, 2001

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Abstract. The Marine Optical Spectrographic (MOS) system is used in two configurations; one for the Marine Optical Buoy (MOBY) and as a shipboard profiler. Both systems are used for vicarious calibration of satellite ocean color sensors, e.g. MODIS, SeaWiFS, OCTS, POLDER, and IRS1-MOS. Band-averaged normalized water-leaving radiances, L_{WN}'s are reported by the MOBY team, corresponding to data sets from MOBY at the Lanai, Hawaii site and various sites for the MOS profiler. For MODIS and SeaWiFS, band-averaged L_{WN}'s are required for the range 412 nm to 670 nm. Here we report on the characterization of stray light in the MOS profiler system. For the first time, a rigorous study was possible using a broadly tunable laser facility. We report preliminary results for correction factors that are required to assess the effect of stray light on the derived up-welling radiance, based on characterizations at NIST of the MOS Profiler.

Marine Optical Spectrograph (MOS) for Marine Optical Buoy (MOBY)

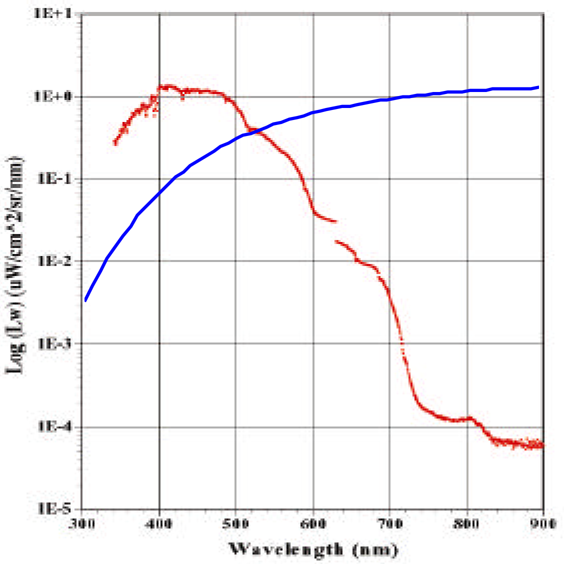
MOS



Blue Spectrograph

Dichroic Beamsplitter

Red Spectrograph



Sphere source for calibration;

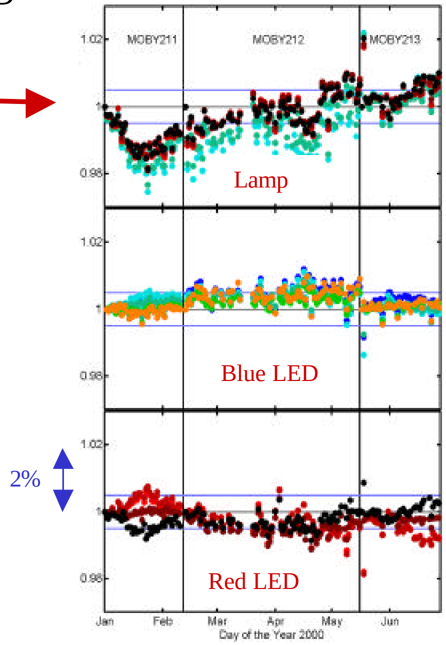
Water-leaving radiance from oceans

• Radiometric Calibrations	• Stability
• Wavelength Calibrations	• Others …..
• Temperature Effects	• **Effects of Stray Light**

Uncertainty Sources

MOBY and Ocean Color

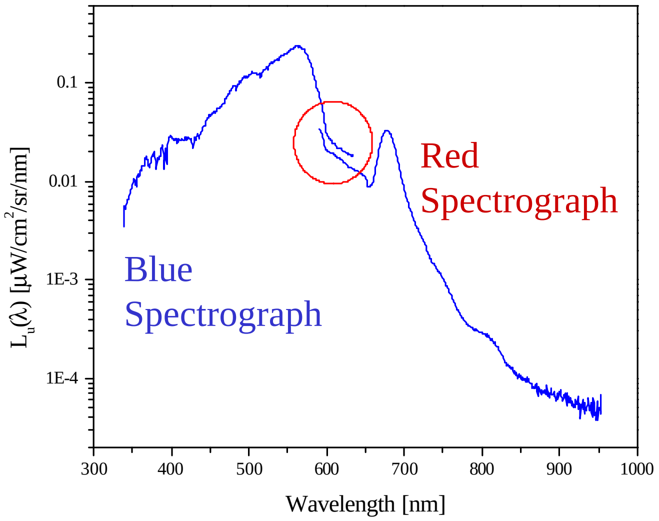
- Time series of band-averaged $L_{WN}(\lambda)$ since 1996
- Wavelength coverage from 350 nm to 950 nm
  - MOS's have dichroic beamsplitter and two single grating CCD spectrographs
- Robust radiometric traceability to NIST
  - source standards are recalibrated every 50 operating hours
  - source standards monitored using NIST-designed filter radiometers
  - annual verification by NIST/EOS calibration validation program
- Excellent stability and repeatability
  - internal calibration sources on MOBY (daily)
  - external sources deployed by divers on MOBY (monthly)
  - all sensors calibrated pre- and post-deployment
- MOBY data sets
  - timed for MODIS and SeaWiFS overpasses (daily)
  - real time data processing
- MOS Profiler
  - during MOBY replacements (every three months)
  - dedicated cruises (MOCE's)

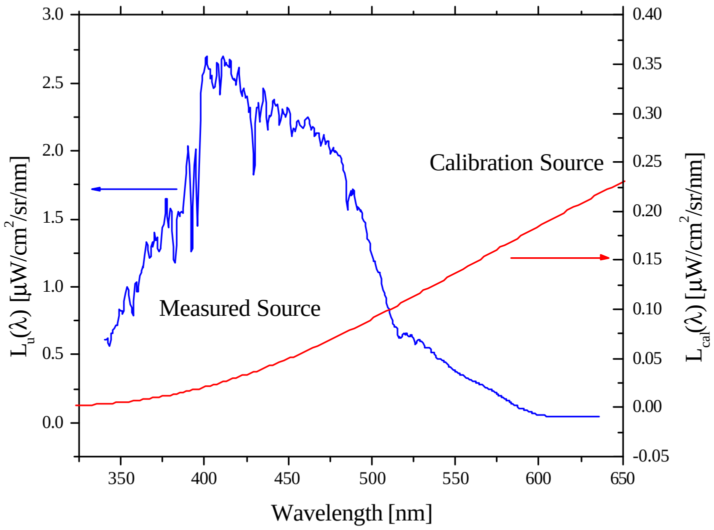


Venice and Monaco Presentations: http://modis-ocean.gsfc.nasa.gov/refs.html

R. A. Barnes et al., "The Calibration of SeaWiFS on Orbit," Proceedings of SPIE, **4135**, 281 (2000).

Motivation for Stray Light Work



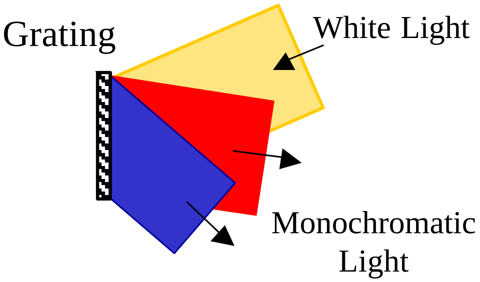


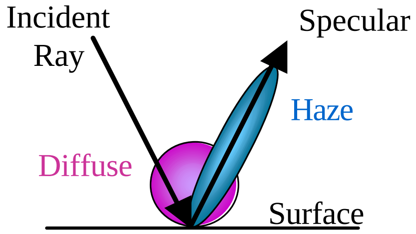
- *Circled Region:* $L_u(l)$ derived using the two spectrographs in MOBY or the MOS Profiler disagree in their region of overlap; degree of discrepancy is depth-dependent
- But at 412 and 440 nm: ±5% agreement with independent filter radiometers

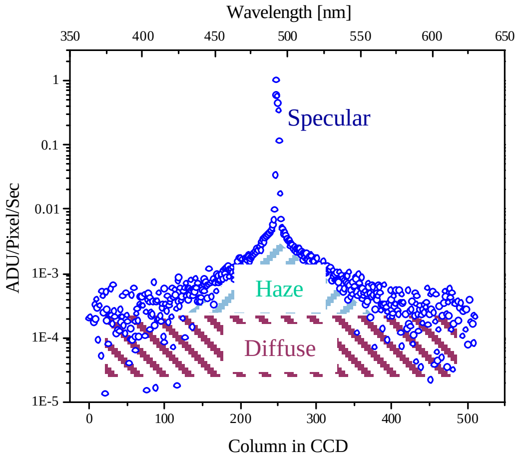
- “Stray light” was suspected (a typical issue with single grating spectrographs used with sources of different spectral shapes)
- NOAA and NIST addressed the problem using tools available at the time
- New facility at NIST provides rigorous solution

Stray Light in Spectrographs

- *Spectrograph operation:* Spectral separation by optical interference of specular reflections from grating—maps to CCD columns
- *Scattering is present:* Not all of the energy is in the specular beam, there is a forward-scattered (haze) and isotropic (diffuse) component (plus scattered light from remaining optical elements)
- *“Out of Band”:* Result is the spectral selection is not ideal (ideal would be a Delta function)
- *Filter Radiometer:* Same effect, but only one “band” per detector
- *Issue* for all single grating instruments

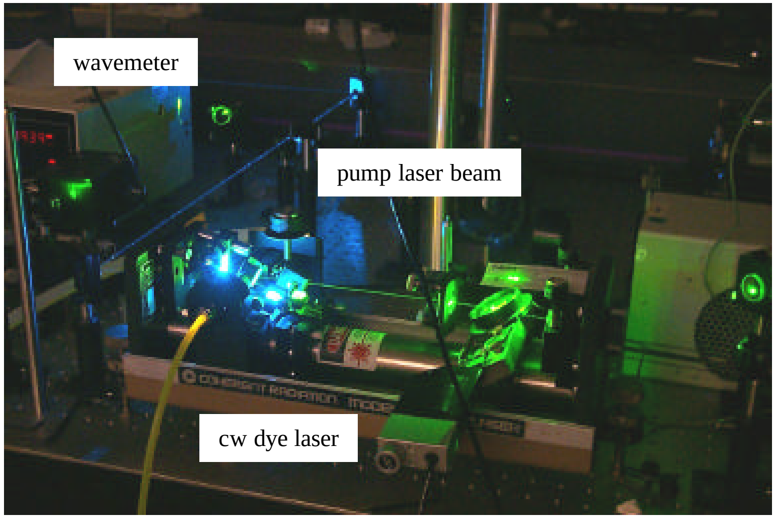


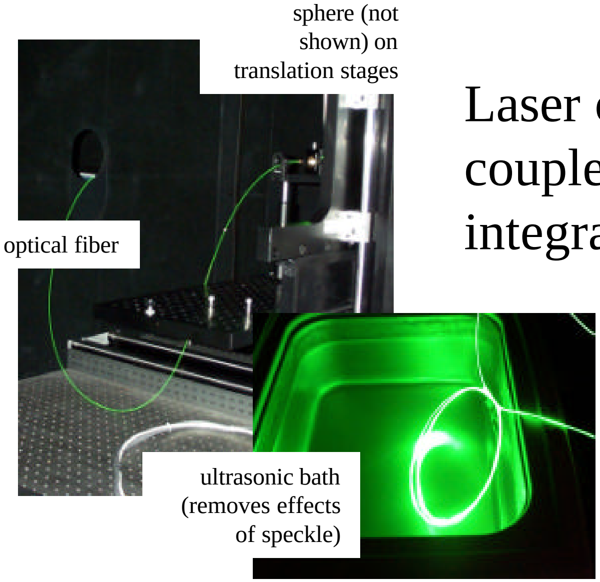




SIRCUS Calibration Facility

A variety of tunable lasers





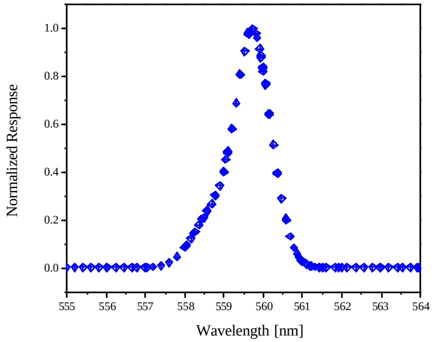
Laser output fiber-coupled into an integrating sphere

- Produces a spatially uniform, monochromatic, broadly tunable source of known radiance (0.1% uncertainty; uses transfer detectors and the NIST cryogenic radiometer)
- With $\Delta\lambda < 0.001$ nm, result is the true radiance (or irradiance) responsivity; high flux levels give excellent signal to noise ratios; optics of radiometer “filled”
- Accurate determination of “in-band” and “out-of-band” component

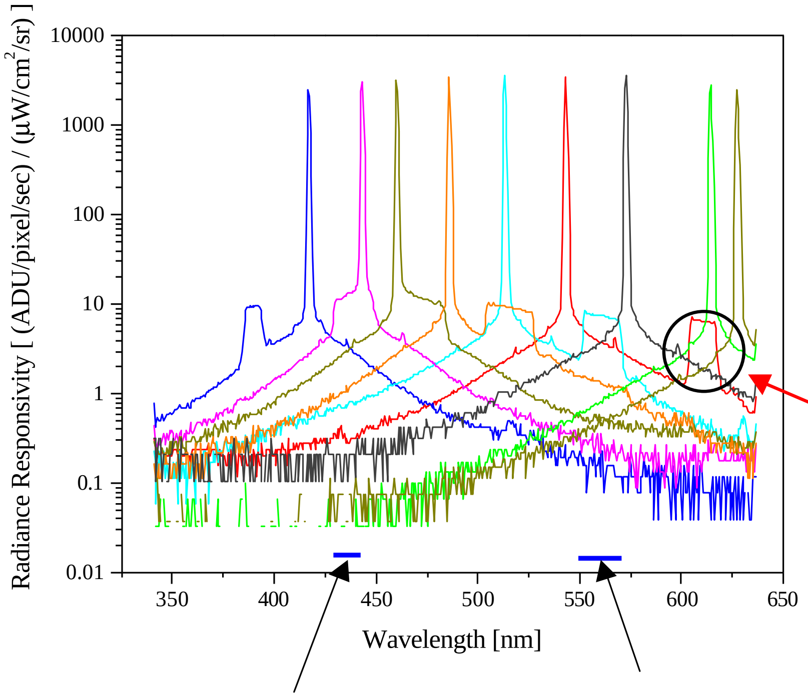
MOS Profiler—Measurements on SIRCUS

Blue Spectrograph

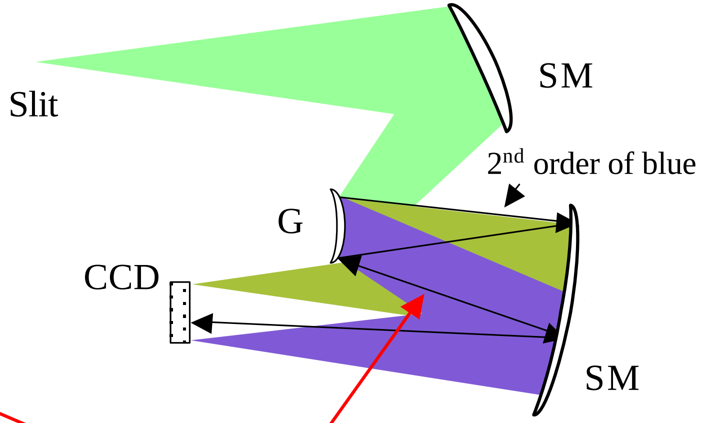
- Preliminary results
- Subset of measurements shown below (response to monochromatic flux)
- Fine scans used to get in-band shape



In-band profile gives bandwidth that is needed for correction algorithm



Two regions of fine scans (about 0.2 nm steps)

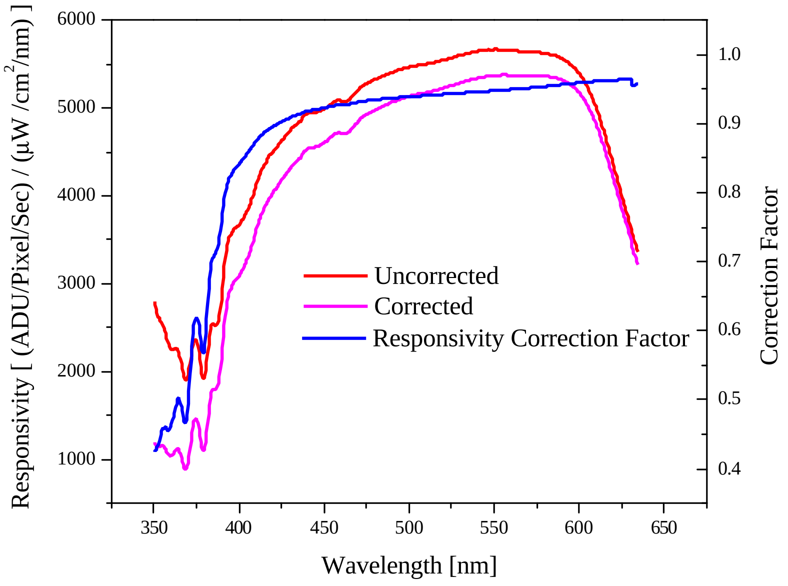


Interreflection of second order causes side lobe (MOS designed to operate in first order)

Stray Light Algorithm

$$R(\mathrm{col}) = [S_T(\mathrm{col}) - S_S(\mathrm{col})]/L_{cal}(\mathrm{col})$$

- Calibrations with broadband sphere or lamp sources give S_T(col), the total signal which includes effects of stray light
- S_S(col) depends on L_{cal}(col) and L_{cal} at all other wavelengths
- The algorithm finds the "true," or "in-band" responsivity R(col) using a model derived from the SIRCUS characterizations
- It is a simple iterative procedure
- Algorithm validated using a colored source of known spectral radiance

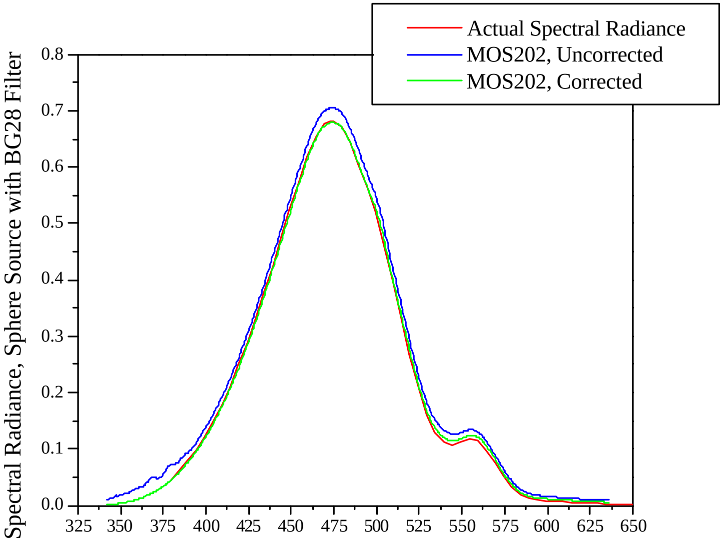


Corrected Radiances

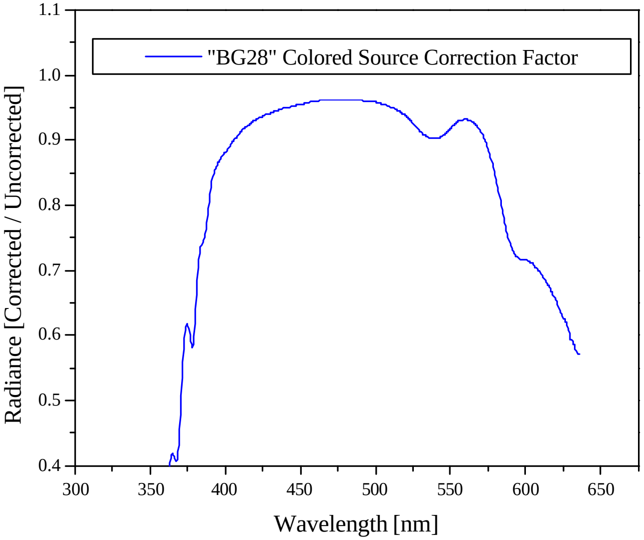
$$L_u(\lambda) = L_{cal}(\lambda)\,[S_T(\lambda) - S_S(\lambda)]_u \,/\, [S_T(\lambda) - S_S(\lambda)]_{cal}$$

- A second iterative procedure is used to determine the corrected water-leaving radiance from the measured count rates
- Tested using a filtered integrating sphere source

Radiances



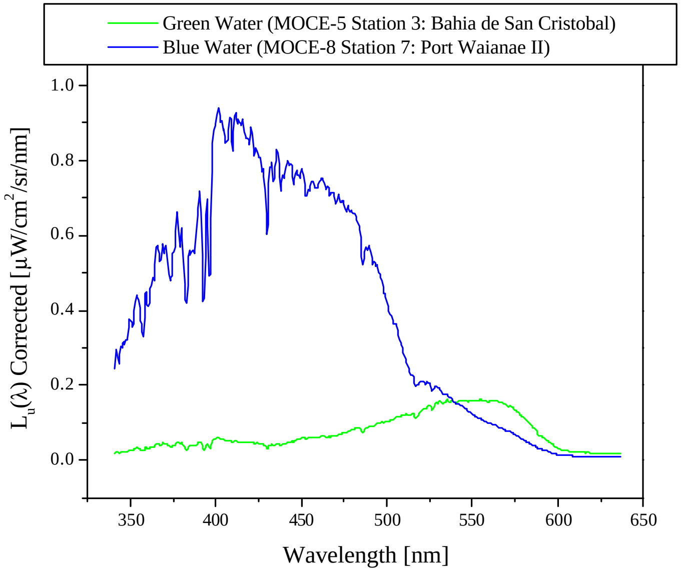
Correction Factor



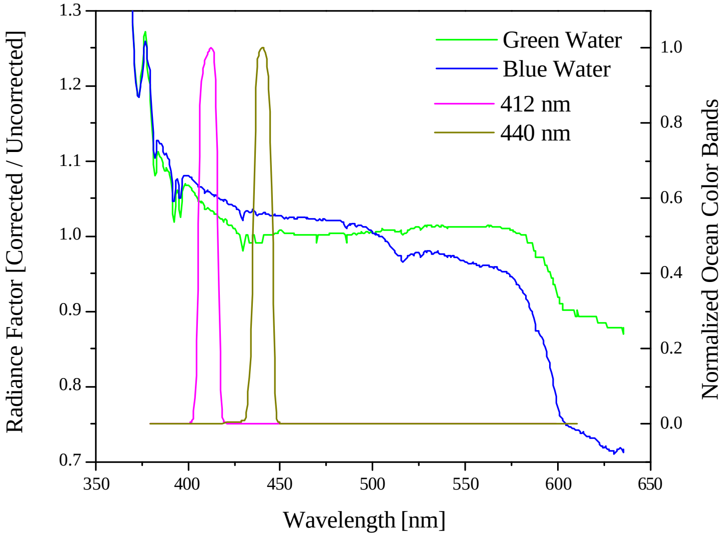
MOS Correction & MOS Data Sets

MOS 202 profiler data from representative measurements of blue and green water (October 1999 and March 2001) were corrected using the MOS SIRCUS results. The correction does not include any effects of the second order interreflections. At 412 nm, the preliminary corrections to the MOS upwelled L_u's are between 3% and 6%.

Corrected radiances



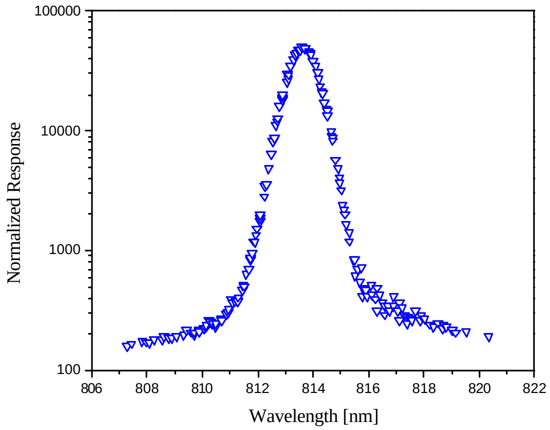
Correction factor & two ocean color bands



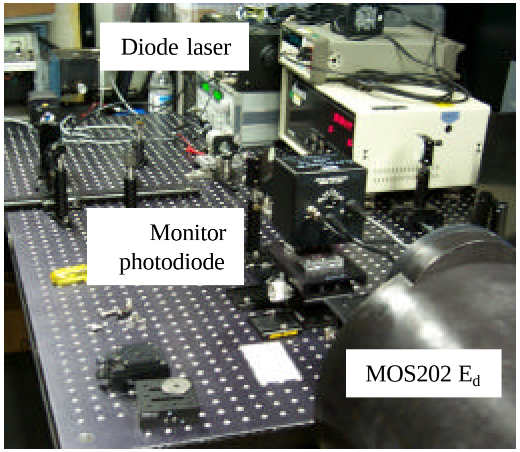
Application to MOBY

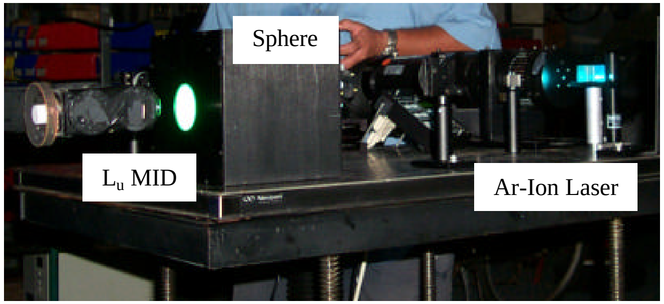
- MOBY vs. MOS Profiler on SIRCUS
  - MOBY stray light characterization **must** be done at Snug Harbor
  - Two MOS's are used on MOBY (interchanged each deployment)
  - The MOS's in MOBY are stable but "unique," so the algorithm correction parameters will be different
  - These MOS's can be studied on MOBY, where MOS is integrated with the fiber optic inputs, or as separate optical systems
- Required Measurements
  - scans with tunable laser for bandwidth
  - measurements with fixed lasers (e.g, 412, 458, 476, 488, 514, 543, 612, and 633 nm) for out of band profile
  - adequate characterization of "2nd order reflections"
  - validation using the absolute colored sphere source
- **MOBY correction factors will be different from the MOS Profiler results presented here**

Tests to Date at Snug Harbor

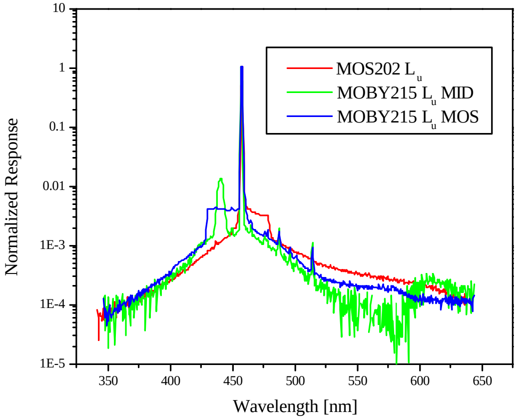


Near infrared tunable diode laser used successfully with E_d and L_u port of MOS profiler





Initial tests with fixed wavelength lasers appear promising



Issues, Plans, and Summary

- Tunable “blue” laser for fine scans of blue spectrograph at Snug Harbor—issue under study
- NIST deployment in July and September 2001 to execute MOBY characterizations
- Validation of stray light correction algorithm using colored source with MOBY’s and MOS’s
- In situ validation using SIRCUS-characterized ocean filter radiometers during a MOCE cruise (winter 2001/2002)
- Fully correctable issue in instruments of proven stability will result in ocean color data set of the highest possible accuracy

Sponsors: NOAA/NESDIS, NIST, and NASA/GSFC (MODIS Science Team, SeaWiFS Project, SIMBIOS Project)

Appendix 4: History of NOAA/MLML Marine Optical System (MOS) Observations.

Cruise: MOCE-8, Ship: R/V Ka'imikai-O-Kanaloa, Location: Hawaii (MOS202cfg08)

Station (#	 Name)	Date (GMT)	Time (GMT)	Latitude (+North)	Longitude (+East)	Depths (dbar)
01	Kalohi Channel	28-Feb-2001	**N.A.**	20.925	-156.989	**NO MOS**
02a	Pala’oa Point	02-Mar-2001	21:25	20.349	-157.247	1,6,11
02b	Pala’oa Point	02-Mar-2001	22:07	20.346	-157.260	1,6,11
03	Kaumalapau Harbor	03-Mar-2001	23:28	20.790	-157.018	1
04a	MOBY Mooring I	04-Mar-2001	21:52	20.870	-157.180	1,6
04b	MOBY Mooring I	04-Mar-2001	22:36	20.870	-157.180	2,5
05	Port Wai’anae I	06-Mar-2001	00:28	20.678	-157.136	1,5,9
06	South of MOBY	06-Mar-2001	21:01	20.678	-157.136	1,2,6,11
07a	Port Wai’anae II	07-Mar-2001	21:48	21.473	-158.522	1,6,11
07b	Port Wai’anae II	07-Mar-2001	22:36	21.473	-158.522	2,6
08	MOBY Mooring II	08-Mar-2001	22:34	20.808	-157.205	2,5,9,11
09	Port Wai’anae III	09-Mar-2001	22:31	21.503	-158.486	2,5

Cruise: MOBY-L69, Ship: R/V Ka'imikai-O-Kanaloa, Location: Hawaii (MOS202cfg08)

Station (#	 Name)	Date (GMT)	Time (GMT)	Latitude (+North)	Longitude (+East)	Depths (dbar)
01	MOBY Mooring I	03-Jun-2001	18:05	20.831	-157.204	1,6 + T.S.
02	MOBY Mooring II	04-Jun-2001	17:00	20.791	-157.185	1,6 + T.S.

Appendix 5: MOS low level Matlab functions

```
 MOS  -  MOS Programs and Functions
Revised 14 June 2001; W. Broenkow, M. Feinholz

Data Acquisition

MOSX                Graphical User Interface program to setup MOS and acquire scan sets

MOS_OPEN_PORT       Open serial port to MOS radiometer set baud buffer
MOS_GETOK           Write CR to MOS until 'OK' is returned perform before other commands
MOS_START           Send FORTH 'DECIMAL STARTUP' command to MOS
MOS_EMPTY           Clear the serial s1.bytesavailable buffer prior to sending FORTH command
MOS_FORTH           Send a FORTH command to port and optionally read response
MOS_COOL            Send FORTH 'BCOOL' and 'RCOOL' to set MOS coolers
MOS_INIT            Initialize MOS using MOS_START and MOS_COOL
MOS_MIRROR          Send MIRROR command to set 'DARK', 'UP', 'DOWN', 'CALIB'
MOS_SETUP           Send FORTH command to set Blue or Red integration, and CCD row parameters
MOS_SPECTS          Send 'BCCD-SETUP' and 'RCCD-SETUP' FORTH commands
MOS_SHUT            Send FORTH 'SHUTDDOWN' command to MOS
MOS_CLOSE_PORT      Close serial port and delete serial object

MOS_GDAD            Read a MOS analog data stream into Vaux variable
MOS_GDAD2           Read a single MOS analog data stream from binary input variable
                    Output Auxiliary data: raw ADU (Pvaux); converted values: (Cvaux)
MOS_GD              Read MOS Radiometric Scan and analog data stream
MOS_LAMBDA          Return wavelength array
MOS_SCANS           Acquire a MOS scan set
MOS_CONVERT_ANALOG  Convert ADU to physical units for single data ADU and code
MOS_CONVERT_VAUX    Convert ADU to physical units for multicolumn Rvaux to Cvaux
MOS_DISPLAY_ANALOG  Display analog data to a handle object or to screen
MOS_PARAM           Display FORTH parameters to screen
MOS_GET_CONFIG      Read an ASCII file containing the MOS station configuration data
MOSX                GUI driven program to acquire MOS data
VAUXTYPMOS_         Explain Variable Auxiliaries for MOS2.M
MOS_GLOBAL          Use this to inspect MOSX.M global variables

Support Functions
RMSE_               Calculate root-mean-square error of spectral scan
CRC_                Cyclic Redundancy Check runs, but disagrees with Richard's CKSM
READGUI             Read 'mosx.m' to print line numbers, variables and callback
                    routines. Essential reading to understand 'mosx.m'.
READACTION          Companion to 'readgui.m'; 'readaction.m' displays all of the
                    line numbers of all actions.
```

Development of a Consistent Multi-Sensor Global Ocean Color Time Series

Robert A. Barnes[1,2,7], Dennis K. Clark[3], Wayne E. Esaias[4], Giulietta S. Fargion[1,2], Gene C. Feldman[5], and Charles R. McClain[6]

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Abstract

The SIMBIOS (Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies) Program was developed to provide a long-term ocean color data set that encompasses the measurements from several satellite instruments. As such, the program is designed to serve as a bridge between previous, current, and future ocean color missions. The previous missions include the Ocean Color and Temperature Scanner (OCTS) and the Polarization and Directionality of the Earth's Reflectances (POLDER) instrument on ADEOS-I. The current missions include the Modular Optoelectronic Scanner (MOS) on IRIS-P3, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) onboard OrbView2, the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multi-angle Imaging SpectroRadiometer (MISR) on Terra. The future missions include MODIS on Aqua, the Medium Resolution Imaging Spectrometer (MERIS) onboard Envisat, and the Global Imager (GLI) and POLDER-II on ADEOS-II. To accomplish this, SIMBIOS has adopted the MOBY (Marine Optical Buoy) ocean platform and the SeaWiFS atmospheric correction algorithm as common references for measurements from the different instruments. This approach by SIMBIOS does not preclude other ocean color reference sites or atmospheric correction procedures. Indeed, it is anticipated that future developments, particularly improvements to atmospheric algorithms, will supercede the current references. The MOBY buoy, however, provides an exceptional set of water-leaving radiances for the intercomparison and merger of measurements from instruments on different satellite platforms. These measurements are traceable to the National Institute of Standards and Technology (NIST), the metrology laboratory for the United States, providing a long-term repeatability for the data set. To date, measurements by OCTS, POLDER, and SeaWiFS have been compared with MOBY to provide a uniform set of ocean color measurements at a single site. In addition, the SeaWiFS Bio-optical Archive and Storage System (SeaBASS) is used by SIMBIOS to provide a set of *in situ* (field collected) water leaving radiance and chlorophyll-*a* measurements for the validation of satellite ocean color measurements at locations away from the MOBY site. SeaBASS and the Aerosol Robotic Network (AERONET) archive also include an extensive set of *in situ* measured aerosol optical thicknesses and other atmospheric parameters to

Proceedings of the International Workshop on Geo-Spatial Knowledge Processing for Natural Resource Management, University of Insubria, Varese, Italy, 28-29 June 2001, A. Belward, E. Binaghi,

provide a basis for examining and improving current atmospheric correction algorithms. All of these components can be combined using the SeaWiFS Data Analysis System (SeaDAS), which is in continuing development and is closely linked to the SeaWiFS and SIMBIOS Projects. SeaDAS allows the user to ingest, process, and display ocean color measurements from different satellite sensors. Currently, SeaDAS can work with data from the Coastal Zone Color Scanner (CZCS), OCTS, POLDER, MOS, and SeaWiFS and can be used to display MODIS data. Planning is underway for the enhancement of SeaDAS to display data from POLDER-II, GLI, and MERIS. In addition, SeaDAS has the capacity to modify a number of atmospheric parameters to provide alternate atmospheric corrections for these measurements. This makes SeaDAS an excellent tool for the testing of upgraded and improved atmospheric correction algorithms. Finally, the SIMBIOS Science Team is working on the optimal procedure for combining the OCTS, POLDER, MOS, MODIS, and SeaWiFS measurements into a single, global ocean color data set as a precursor to an expanded data set that includes other current and future satellite instruments. There is a proposed climatology that provides monthly global chlorophyll-*a* and related ocean color fields on a 9 kilometer grid, using a blend of *in situ* and satellite measurements. The use of MOBY as a normalizing reference for this time series should remove problems with the selection of an appropriate reference from the set of satellite instruments.

Keywords: Data set, ocean color, multi-satellite, global, long-term

1. Introduction

For Earth observations from space there is a distinction between monitoring (the routine observation of processes for operational forecasting, early warning, or management) and long-term science (the study of environmental processes that occur on long time scales). The SIMBIOS Program, which is modeled after the SeaWiFS Project, is designed in part to serve the latter purpose by developing a consistent time series of ocean color from multiple satellite sensors. In addition, the program gathers *in situ* information to support satellite measurements. The ocean color data from these measurements will serve as a framework for scientific studies of ocean ecosystems.

The science issues behind ocean color studies can be summarized as three broad objectives. The first is the characterization of the variability, both spatial and temporal, in the structure of the phytoplanktonic community and its links with higher trophic levels as well as with ocean biochemistry. The second is the prediction of the ocean's biogeochemical response to and its influence on climatic change. And the third is the development of the scientific basis necessary to manage the sustainable resources of the coastal marine ecosystem effectively. In addition to providing measurements of the distribution of phytoplankton, ocean color data can be used to provide estimates of some important ocean processes relevant to air-sea fluxes, particularly primary productivity. An understanding of the patterns in ocean biology will provide a basis for an understanding of biological processes within the ocean.

Biomass turnover rates for plankton ecosystems are one hundred times faster than those for terrestrial ecosystems, leading to a close relationship between upper-ocean ecology and physical forcing. For example, coupled ocean and atmospheric models show that changes in the phytopkanktonic community structure and the resulting elemental interactions can drastically affect the rate of carbon dioxide increase in the atmosphere. Ocean ecosystems also change on decadal time scales in response to climate change. Moreover, the large time and space scales associated with ocean biogeochemistry and circulation can be disrupted on intermediate time scales, such as those of the El Ninõ/Southern Oscillation. This coupling of large and small time scales leads to the fundamental sampling requirement of global-scale, long-time series (decades) at moderate time and spatial scales (days and kilometers).

Currently, the fundamental geophysical products are diffuse attenuation, phytoplankton chlorophyll-*a*, CDOM, and suspended sediments. New MODIS products include chlorophyll fluorescence, calcite, and primary productivity. However, it is expected that this list will expand as more complete *in situ* measurements and semi-analytical models allow new parameters to be estimated. Currently most products are based on empirical correlations between the ratios of water-leaving radiances at a few wavelengths. A more rigorous approach to the application of ocean color measurements will come from an understanding of the inherent optical properties of each of the optically significant components of seawater.

It is clear that many, if not most, Earth science problems require an interdisciplinary approach for their understanding and prediction. For studies of ocean primary productivity, for example, there are preliminary models of how various physical processes affect light and nutrient availability for phytoplanktonic communities (NASA, 1987). The patterns of primary forcing, as well as the patterns of ocean color, will be necessary to provide the patterns of primary production – and, ultimately, to provide an understanding of the key mechanisms behind the processes.

No single data set will suit all scientific requirements. Studies of river mouths and estuaries will require measurements with spatial sampling requirements that challenge global satellite sensors. And studies of coastal ocean processes will require far more intensive temporal sampling than the open ocean, because of their small characteristic scales. For example, tidal forcing is an important component of the coastal environment, and satellite measurements from sun-synchronous orbits will shift this high-frequency variability into lower frequencies (NRC, 2000a). Ultimately, individual ocean color data sets must be constrained by their applicability to one or a few related Earth science problems.

Finally, the generation system for the data set must be constructed in a manner that scientists not directly involved in its establishment can contribute to the development of new algorithms and new data (NRC, 1995). Accessibility by the fullest possible user community is critical for the maximum use of the data and for meeting the science objectives for the data set. For more than a decade, the SeaWiFS Data Analysis System (SeaDAS) (Baith et al., 2001) has developed user friendly data processing and display software for several ocean color instruments, including CZCS, SeaWiFS, OCTS, POLDER, MODIS, and MOS. This software is freely available for download from the SeaDAS website (http://seadas.gsfc.nasa.gov), and it has the flexibility to provide executable programs for those who only need the basic capabilities as well as source code for those who wish adapt the code to insert alternate algorithms. The SeaDAS team, with the assistance of the SeaWiFS and SIMBIOS Projects, is working to develop new ocean color data products and enhanced accessibility to these data for an expanding user community.

The ideas presented in this introduction are not unique to the SIMBIOS Program, nor, for the most part, were they originated by the project. To a large extent, these ideas are direct reflections of issues and recommendations in reports of the National Research Council (NRC, 1995, 1999a, 1999b, 2000a, 2000b), which provide guidelines to NASA for long-term climate data sets.

2. Ocean Color Program Objectives

Individual spaceborne ocean color sensors, including SeaWiFS, routinely measure meso-scale oceanic phenomena, such as the phytoplankton bloom around the Marquesas Islands (Signorini et al. 1999), where the bloom extended from 500 to 1000 km downstream of the islands in the flow of the South Equatorial Current. These sensors can also measure the variability of chlorophyll-*a* on basin scales (Murtugudde et al. 1999) and can provide measurements of the near surface phytoplankton chlorophyll-*a* concentration globally over the time scale of the El Ninõ/Southern Oscillation (Behrenfeld et al. 2001). Indeed, models of oceanic primary production have been greatly aided by global-scale satellite observations of phytoplankton biomass (Field et al. 1998) – as have terrestrial models by remote sensing of the land. A long-term, multi-platform ocean color data set must provide the basis for studies such as these, and more, particularly for studies over time scales that extend beyond the operational lifetimes of individual sensors.

The coordination of a long-term ocean color data set by the SIMBIOS Program, with guidance from the International Ocean-Colour Coordinating Group (IOCCG), is a scientific and technological experiment requiring collaboration by the international community. The development of the data set as a research tool must be focused on a set of key unanswered scientific questions – questions about the ocean environment that will be used to formulate the observations and analyses required for their resolution. Without this focus, research on the complex and varied ocean system is likely to be fragmented and inconclusive. However, this focus must be balanced by the knowledge that there will be surprises in future ocean color research. The data set must be sufficiently broad to catch the unexpected, if that is possible (NRC, 1999a). This balance is a principal challenge to the coordination of the data set. In addition, answers to the key scientific questions will require an interdisciplinary approach, since oceanic biological processes are complex. The ocean color data set cannot stand alone. It must be coordinated with other atmospheric and oceanic observations.

Science Objectives

The ocean color data set is a small, but important, constituent of NASA’s Earth Science Program. The essence of that program can be summarized in five fundamental science questions (NASA, 2000). How is the global Earth system changing? What are the primary forcings of the Earth system? How does the Earth system respond to natural and human-induced changes? What are the consequences of change in the Earth system for human civilization? Finally, how well can we predict changes in the Earth system that will take place in the future? Ocean biogeochemistry plays a fundamental role in the Earth system, since through photosynthesis, the ocean’s phytoplankton take up atmospheric carbon dioxide, sequestering it in the deep ocean, where it is slowly buried as sedimentary carbon. Currently, less than half of the carbon dioxide released into the atmosphere by combustion of fossil fuels and deforestation remains in the atmosphere. The remainder is sequestered in oceanic and terrestrial sinks. The ocean is part of a long-term biological buffering process for carbon, wherein various damping and feedback mechanisms in the Earth system regulate pulses of carbon from anthropogenic and natural sources. On a geologic time scale, the current anthropogenic release is a sudden pulse into the system. The buffering mechanisms are incompletely understood at best, and their capacity to cleanse the Earth system of the modern human pulse of carbon is not known.

For the oceans, an understanding of biogeochemical processes starts with a knowledge of the distribution and variability of phytoplankton in the surface waters of the world’s oceans. The ocean color data set provides the basis for temporal and spatial variability studies with time periods from days to decades and with spatial sizes from mesoscale to global. The spatial scale requires the use of satellite-based observations, and the temporal scale requires the use of measurements from more than a single ocean color satellite instrument. These patterns of ocean phytoplankton concentrations provide a fundamental input to physical-biogeochemical process studies, including those of photosynthesis and respiration and of interactions at the air-sea interface. These processes are part of ocean primary production, the first step in the sequestering of excess atmospheric carbon dioxide. In addition, phytoplankton are the basic component of marine ecosystems, and phytoplankton patterns provide the basis for mesoscale and global marine ecosystem studies. We do not assume that the ocean color data set provides answers to the questions about the role of the oceans in the Earth system. However, the biological patterns in the data set provide information and understanding that are requisite to the development of those answers.

Operational Objectives

The calibration and validation programs for individual missions have a wide range of comprehensiveness, making international cooperation imperative to ensure high quality data. Fundamentally, the data set must have consistent products (chlorophyll-*a*, etc.) – consistent both in space and time. This implies a consistent derivation of those products, within the limitations of sensor-to-sensor differences. In other words, the pathway from the top-of-the-atmosphere radiance at the satellite instrument's input aperture to the geophysical data product should be as consistent as possible from instrument-to-instrument. Otherwise, it is problematic whether inconsistencies in the data products from different sources can be understood and rectified. And it is problematic whether an inconsistent ocean color data set will serve to meet the program's scientific objectives. There is, of course, no guarantee that a given pathway from top-of-the-atmosphere measurements to ocean data products is the optimal one. The evolution and improvement of the data set closely follows the development of improved algorithms. However, for any one version of the data set, a single consistent set of algorithms is essential.

There must be a temporal continuity – from satellite instrument to satellite instrument – in the data set. Sensor characterization and an effective, ongoing program of sensor calibration and validation are essential to separate the effects of changes in the ocean system from those from changes in the observing system. This is a particular challenge, since there are few examples of continuous data records based on satellite measurements where data quality is consistent across changes in sensors, even when copies of the sensor design are used (NRC, 2000a). In the case of ocean color, only the two MODIS instruments have a common design. In addition, since the ocean color data set will be used to examine changes in ocean bio-optics over time periods of decades, it is imperative to preserve the calibration and operating information for each ocean color sensor, as well as metadata and ancillary data fields, in a manner that allows reprocessing. However, future reprocessings will require more than just the calibration data sets. For this reason, the SeaWiFS Project has developed an extensive set of technical memorandums to provide the information necessary to apply the calibration and validation techniques. Without such documentation, reprocessing attempts may prove problematical. These caveats for satellite measurements apply equally to the *in situ* instruments used to calibrate and validate them.

There must be a consistent, objective method for merging the data products from individual satellite instruments. In addition there must be a consistent, objective method for merging the data products from satellite and *in situ* instruments. The added value from *in situ* measurements makes their inclusion in the data set imperative. As with the data reduction algorithms, there is no guarantee that a given data merger scheme is the optimal one. And as with the case of algorithms, the evolution and improvement of the data set will follow the development of improved data merger methods. However, for any one version of the data set, a single consistent method of merging data products from different sources is essential.

Finally, as advocated by the US National Research Council for NASA's Post-2002 Earth observing missions, the ocean color data set should be developed under a sound scientific strategy – including supporting observational, data management, and analytical activities – that is: 1. Agile – to enable timely response to technological changes or to changing research priorities; 2. Focused – to enable progress on answering specific, central scientific questions about ocean bio-optical phenomena; and 3. Coherent – to enable a balanced (that is, space-based and *in situ*) and integrated, interagency and international response to ocean bio-optical issues (NRC, 1999b).

3. Implementation

Adaptability and flexibility are essential for the information system containing the ocean color data set if it is to be useful in a world of changing technical capabilities and scientific requirements. Current user demands on the system are generally known at best, and future user-driven needs are unknown. Similar considerations also apply to the data set, as well. It must be flexible enough to accommodate new data products that cannot yet be envisioned. And, in particular, it must have the capability for rapid reprocessing, starting from the on-orbit measurements and ending with the derived geophysical data set. For the creation of the ocean color data set, the SIMBIOS Program has developed a set of key tools: 1. a comprehensive bio-optical data base; 2. a program to evaluate different atmospheric correction algorithms; 3. a program to link the calibrations of individual ocean color satellite instruments; 4. a program (including calibration cross-calibrations and measurement protocols) to develop a consistent *in situ* calibration and validation data set for the satellite measurements; 5. alternate algorithms to convert radiometric measurements to derived geophysical products; and 6. alternate methods to combine ocean color measurements from different sources into a single data set.

Comprehensive Bio-Optical Data Base

Ground based measurements and measurement networks support and extend space-based observations. They are critical for algorithm development and for calibrating and validating satellite measurements. In addition, they often provide the high-resolution observations in both time and space needed to carry out the process studies that elucidate the mechanisms underlying ocean biochemistry. For example, Gregg and Conkright (2001) have combined about 70,000 surface observations with remotely-sensed data from the Coastal Zone Color Scanner (CZCS) to provide an enhanced set of seasonal chlorophyll-*a* climatologies for the CZCS era (1978-1986). The *in situ* and satellite data were merged using the Conditional Relaxation Analysis Method previously applied by Reynolds (1988) and Reynolds et al. (1989) to ameliorate biases in satellite sea surface temperature measurements. In one sense, the blended analysis of Gregg and Conkright (2001) uses the satellite chlorophyll-*a* field as an interpolation function for the *in situ* observations. In another sense, the blended analysis provides a vicarious calibration of the CZCS data products, which suffer from the limited success of the CZCS on-orbit radiometric calibration (Evans and Gordon, 1994). Generally, the CZCS appears to underestimate chlorophyll-*a* concentrations globally by 8 to 35%, and regionally, the blended analysis returns chlorophyll-*a* values that are often 20 to 40% and occasionally more than 100% greater than those from the CZCS (Gregg and Conkright, 2001). However, for large areas of the ocean gyres, the data merger was not possible, due to the lack of *in situ* observations. Ultimately, global ocean color data sets must be comprised of both *in situ* and space-based observations to ensure the optimal quality of the data.

In situ ocean measurements have an equally critical function in the development of the algorithms that convert radiometric measurements (water leaving radiance or surface reflectance) to geophysical data products (chlorophyll *a* and others). The quality of these conversion algorithms is no better than that of the data sets of ocean properties used to create them. The application of these algorithms to different oceanic locations (clear ocean basins or turbid coastal waters) is no better than the *in situ* data sets from the individual locations. And the development of these algorithms and of the associated models of oceanic optical properties (Garver and Siegel, 1997, O'Reilley et al. 1998) is the reason for the radiometric measurements. In addition, subsequent *in situ* measurements will serve to validate ocean color algorithms after their development. *In situ* measurements are indispensable to any ocean color data set.

Since 1991, the SeaWiFS Project has worked to develop a database of *in situ* near-surface chlorophyll-*a* measurements – SeaBASS (the SeaWiFS Bio-optical Archive and Storage System) (Werdell et al. 2000). Since 1997, the original SeaWiFS database has been expanded to include *in situ* measurements by investigators and science team members of the SIMBIOS Program, making the archive a joint venture of the two projects. SeaBASS is a repository for *in situ* optical and pigment data products used for the validation of measurements from SeaWiFS and from other ocean color missions – and for the development of new ocean color algorithms. This latter function of SeaBASS is particularly important, since ocean color algorithm development is essentially limited by the availability of *in situ* measurements. Currently, the SeaBASS data set includes approximately 20,000 near surface chlorophyll-*a* measurements taken from more than 650 field campaigns. These data extend back to 1975, with the vast majority of the measurements from 1990 to date, and with new data received and placed in the archive on a regular basis.

All of the data from the field campaigns in SeaBASS is checked for proper formatting, relevant documentation, and associated calibration files. Some rudimentary quality control checks are run on the field data, and the results of these checks are resolved to the satisfaction of the experimenters.

SeaBASS includes a data archive and two relational databases (RDBs). The archive includes the near-surface chlorophyll-*a* measurements discussed above plus additional bio-optical data products, including phytoplankton pigments, total suspended particulate matter, and chromatic dissolved organic matter. As part of the SIMBIOS Project, the SeaBASS data archive has been expanded to include atmospheric measurements, principally aerosol optical thickness measurements from sun photometers. This archive can be searched using several online search engines and the bio-optical RDB. In addition, there is a separate historical pigment RDB, which contains over 300,000 records of phytoplankton pigment that can be searched online. The information in the historical pigment RDB is separate from the SeaBASS archive, and the historical pigment data are not currently maintained.

The historical pigment RDB is openly available to the public. However, access to the SeaBASS data archive and the bio-optical RDB are restricted to SeaWiFS Project and SIMBIOS Science Team members and to other approved individuals (including members of other ocean color instrument teams and voluntary data contributors) for advanced algorithm development and data product evaluation purposes. Further information on this policy and an application for a SeaBASS account registration are available at the SeaBASS website (http://seabass.gsfc.nasa.gov). The comparison of *in situ* chlorophyll-*a* measurements with SeaWiFS-derived values is discussed by Bailey et al. (2000) .

Atmospheric Correction Algorithm Evaluation

Current ocean color algorithms derive oceanic optical properties in a two step process, an atmospheric correction followed by a bio-optical algorithm to estimate the water properties. For ocean color measurements by satellite instruments, the greatest portion of the upwelling radiance at the top-of-the-atmosphere comes from the atmosphere itself. For the atmospheric correction algorithm, portions of the upwelling radiance, such as that part of the solar flux scattered upwards by air molecules, can be calculated exactly. However, the calculation of the upwelling radiance from atmospheric aerosols requires knowledge of both the aerosol type and amount. In current ocean color algorithms, the aerosol properties are determined using measurements in the near infrared, where the ocean surface is nearly black. Based on the properties determined from these measurements, a model of the aerosol type is selected from a set of candidate models, and the aerosol-based upwelling atmospheric radiance in the ocean color portion of the spectrum is calculated.

Current atmospheric correction algorithms, such as the one for SeaWiFS (Gordon and Wang, 1994), work reasonably well over most of the oceans, where the aerosols scatter the solar flux and absorb it weakly. However, there are regions, such as the Western Mid-Latitude North Pacific and the Eastern Tropical North Atlantic where the prevailing winds carry mineral-laden dust and anthropogenically-generated carbonaceous aerosols over the ocean. These aerosols absorb solar radiation in the ocean color portion of the spectrum, and the current atmospheric correction algorithms fail to account for it. This failure can be traced to two causes (Gordon, 1997). First, the spectral dependence of the aerosol scattering visible portion of the spectrum depends on the vertical distribution of the aerosol, whereas this is not the case in the near infrared where the aerosol properties are determined. Second, the spectral variation of aerosol scattering in the near infrared provides no information on the aerosol's absorbing characteristics, since they depends primarily on the aerosol's size distribution – a property that cannot be determined from the current set of near infrared measurements.

New, one-step ocean color algorithms are under development (Gordon et al. 1997, Chomko and Gordon, 1998). These algorithms retrieve the atmosphere and water properties simultaneously. These retrievals require both a first-guess aerosol model and a first-guess water model. There are fewer parameters in the models than there are measurement wavelengths by the ocean color instrument – and the model parameters are varied systematically until the difference between the measured and calculated results are minimized. The aerosol models use a three-component log-normal aerosol size distribution (Shettle, 1984) or a Junge power-law distribution. Based on these distributions, the scattering and absorption properties are computed using Mie theory. These new one-step algorithms show a significant improvement in the atmospheric correction of ocean scenes containing absorbing aerosols. However, because of their iterative nature, these algorithms are currently too computer intensive for use with global ocean color data sets.

At the hearts of both the one-step and two-step ocean color algorithms are sets of aerosol models. The validation of the selection process for the aerosol models in these algorithms and the validation of the properties of the aerosols in the models are both central to the creation of an optimal ocean color data set. The principal source of *in situ* aerosol observations has been AERONET, the Aerosol Robotic Network (Holben et al. 1998), a network of ground-based automated sun photometers. Since the majority of the AERONET stations are at continental locations, the SIMBIOS Project has augmented the AERONET network with instruments at 13 additional coastal sites. The initial emphasis for SIMBIOS (Fargion et al. 2001) has been the use of the sun photometers for comparisons of *in situ* aerosol optical thicknesses with those derived from ocean color satellite measurements. Aerosol optical depth is a standard product of the atmospheric correction algorithms for the ocean color instruments, and it is a primary geophysical product for sun photometers. In addition, the SIMBIOS Project has concentrated on the development of protocols for the calibration of sun photometers and sky radiometers and of protocols for the analysis of the derived aerosol optical thicknesses, plus procedures for screening *in situ* optical thicknesses for comparisons with satellite-based measurements (Fargion et al. 2001). Comparisons of the *in situ* aerosol optical thicknesses with SeaWiFS results indicate a miscalibration of about 5% in the near infrared bands of the satellite instrument, giving satellite-based aerosol column amounts that are consistently greater than those from the sun photometers.

Sun and sky radiance measurements from the sun photometer instruments also provide optical properties for the atmospheric aerosols, properties that are basic to the atmospheric corrections of satellite ocean color measurements. In particular, a set of inversion algorithms has been developed that retrieves the aerosol size distribution over a wide range of sizes (0.05 to 15 μm) together with the spectrally dependent single-scattering albedo (Dubovik and King, 2000, Dubovik et al. 2000). The aerosol size distribution is a principal parameter in the atmospheric models for the one-step ocean color algorithms (Gordon et al. 1997, Chomko and Gordon, 1998), and the sun photometer derived distributions provide a valuable check of the assumptions within these algorithms. In addition, a climatology of aerosol size distributions at the SIMBIOS sites will provide a basis for refinements to the atmospheric correction portions of the one-step algorithms. Results for the aerosol size distribution and single scattering albedo at the SIMBIOS site in Bahrain (Smirnov et al. 2001) provide a start for these climatologies.

For the current, two-step ocean color algorithms, the single scattering albedo is the principal aerosol property derived from the satellite instrument's measurements in the near infrared (Gordon and Wang, 1994), and it is the wavelength dependence of the algorithm-based albedo that is used to provide the aerosol-based upwelling atmospheric radiance for the ocean color bands. As with the aerosol size distributions, the *in situ* single scattering albedos provide an independent check of the ocean color algorithms, as well as the climatological basis for improved scattering models in the algorithms. The atmospheric portion of the SeaWiFS two-step ocean color algorithm continues to be improved and updated (Wang, 2000). The SIMBIOS Project is pursuing the use of sun photometer results in this process. It is anticipated that these studies can be applied to the atmospheric algorithms for other ocean color instruments as well.

Satellite Instrument Calibration

For long-term measurements of climate variables, effective on-going programs of sensor calibration and validation, sensor characterization, data continuity, and strategies for ensuring overlap across successive sensors are essential (NRC, 2000a). Individual ocean color satellite instruments use individual characterization and calibration methods, and there will be differences in the on-orbit measurements from these instruments. A multi-platform ocean color data set requires a means of unifying measurements from different satellite sensors. For example, as part of the pre-flight calibration activities for OCTS and SeaWiFS, the SeaWiFS

Transfer Radiometer (SXR) was used as part of a radiometric measurement comparison of the integrating sphere used to calibrate OCTS (Johnson et al. 1997) and as a calibration standard for the SeaWiFS integrating sphere (Johnson et al. 1999). The EOS Project has developed a similar transfer radiometer to cross-calibrate MODIS, the other EOS sensors, GLI, and MERIS. These round-robin measurements serve to link the prelaunch radiometric calibrations of different ocean color satellite instruments. It is also important to understand the operating characteristics of the satellite instruments, such as their susceptibility to spatial stray light from bright targets (clouds and land surfaces) adjacent to ocean scenes. For the SeaWiFS sensor, the instrument characterization has been extensively documented in the SeaWiFS technical memorandum series. In addition, the SIMBIOS Project is proceeding to unify the on-orbit calibration of SeaWiFS with other instruments using water-leaving radiances from MOBY as a surface truth reference. This process does not preclude the need for surface truth measurements at other sites, nor does it preclude the need for a thorough characterization of each satellite sensor, nor does it preclude the need for an active program of on-orbit calibration for each sensor.

Direct On-Orbit Calibration

Individual ocean color instruments use a variety of techniques for determining the calibration of their measurements on orbit and monitoring changes in sensor performance. For OCTS, the on-orbit calibration relied primarily on internal calibration lamps and on underflights by a calibrated airborne sensor as an absolute reference (Shimada et al. 1999). For POLDER, the in-flight radiometric calibration did not rely on any on-board calibration device (Hagolle et al. 1999). POLDER used atmospheric molecular scattering as an absolute reference and used measurements of ocean sun glint and high altitude cloud-tops for relative (band-to-band) calibrations. In addition, POLDER used measurements of a set of ground sites to monitor changes in the instrument over time. For SeaWiFS, the laboratory calibration was carried to orbit using the transfer-to-orbit experiment (Barnes et al. 2000), and instrument changes are determined by using the moon as an external diffuse reflector (Barnes et al. 1999). For SeaWiFS, the only absolute portion of the calibration chain is the calibration in the laboratory before launch. For MODIS, and for several instruments to follow, the on-orbit calibration reference is an onboard diffuse reflecting plaque, the changes of which are determined by a ratioing radiometer (Guenther et al. 1996). For each of these instruments, the estimated uncertainty in the top-of-the-atmosphere measurements is about 5% or less, and for each of these instruments there is a record of its characterization and calibration.

Vicarious Calibration

With the review of the Coastal Zone Color Scanner (CZCS) calibration by Evans and Gordon (1994), it has become clear that onboard measurements alone are inadequate to provide good ocean color measurements. In principle, this is due to the nature of the measurements. In the visible, the ocean is dark, and the majority of the flux at the top-of-the-atmosphere (90% or more) comes from the atmosphere. Since the removal of the atmospheric radiance is an essential part of ocean color measurements, the radiance from the ocean is calculated as the small difference between two large values. Thus, an error of 1% in the top-of-the-atmosphere radiance can cause an error of 10% or more in the derived radiance at the ocean surface. As a result, the SeaWiFS ocean color data are vicariously calibrated. Here, the term vicarious has the definition – "as seen through the eyes of another." SeaWiFS data are calibrated at a single point on the globe, off the Hawaiian Island of Lanai, using comparisons with the water-leaving radiances from the MOBY buoy (Clark et al. 1997). For the visible bands, vicarious calibration coefficients adjust the top-of-the-atmosphere radiances from the instrument until the derived water-leaving radiances agree with those from MOBY. This is a calibration of the "instrument/atmospheric correction algorithm system" for SeaWiFS, since both parts of the system are required to derive the water-leaving radiance. Included in the SeaWiFS Post-Launch technical memorandum series (McClain et al. 2000a, 2000b) are outlines of the suite of procedures and quality control tests used for the postlaunch calibration and validation of SeaWiFS.

The SIMBIOS Project has developed software for processing measurements from several ocean color sensors. This set of algorithms (MSL12) is based on the standard SeaWiFS atmospheric correction (Gordon and Wang, 1994, Wang, 2000). It can be applied to other sensors, such as OCTS and POLDER, giving a consistent atmospheric correction for each instrument. Since OCTS and POLDER flew in tandem on the ADEOS spacecraft and made several measurements of the MOBY site during their operational lifetimes, Wang et al. (2001) have performed a vicarious calibration of these instruments using *in situ* data from MOBY. After the calibration, there are no obvious differences in the OCTS and POLDER-derived ocean products, based on common measurements by the two instruments over the Sargasso Sea and the Bermuda area. These results indicate that the OCTS and POLDER ocean color sets data can be compared and merged in the sense that there is no significant bias between them. These results also indicate that it may be possible to cross-calibrate instruments on different spacecraft – such as SeaWiFS and MODIS – using MOBY as a common calibration reference. In this case, a detailed analysis by the SIMBIOS Project is probably unnecessary, since MODIS ocean color data products are vicariously calibrated at MOBY, in a manner similar to SeaWiFS.

***In situ* Instrument Calibration and Protocols**

Ground based measurements are critical for calibrating and validating ocean color measurements from space. The SIMBIOS Project is continuing the series of SeaWiFS intercalibration round-robin experiments (Johnson et al. 1999) with a program cross-calibrations of laboratory sources using a travelling transfer radiometer, the SXR2. This instrument is a second-generation version of the SXR, which was used in a radiometric measurement comparison of the OCTS visible and near infrared integrating sphere (Johnson et al. 1997) as part of the pre-flight calibration and validation activities for OCTS and SeaWiFS. The SXR2 shares the spectral responses of the SXR; however, the SXR2 has been designed to view reference sources for *in situ* ocean color instruments, reference sources that are less bright than those used to calibrate satellite instruments. The SXR2 was calibrated in early 2001 at the NIST facility for Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) (Brown et al. 2000). SIRCUS used tuneable laser sources to provide monochromatic light flux for the set of wavelengths over the spectral response ranges of the SXR2. In addition, the SXR2 was calibrated at NIST using a standard broadband source. This year, SXR2 cross calibration measurements have been made at the US Naval Research Laboratory, the Scripps Institute of Oceanography, and the University of California Santa Barbara. Comparisons with other institutions are being scheduled. The SIMBIOS Project has developed the SXR2 as a cross-calibration tool for use by the ocean color community.

The continuity and consistency of the global data set is a direct reflection of the continuity and consistency of the *in situ* measurements used to calibrate and validate it. This is the premise for the SIMBIOS cross-calibration program. In addition, a standard set of measurement protocols is indispensable for the required consistency in the *in situ* calibration data set. The development of *in situ* measurement protocols has be a primary focus of both the SeaWiFS and SIMBIOS Projects (see Fargion and Mueller (2000) and the references cited therein). It continues as a primary focus in the development of the multi-sensor global ocean color data set.

4. Creating a Multi-Sensor Global Ocean Color Data Set

The work of Wang et al. (2001) has demonstrated the feasibility of merging the ocean color data sets from OCTS and POLDER. And the SIMBIOS Program is using the measurements from these instruments to test techniques for merging global data sets. However, the operational lifetimes of these instruments (November 1996 to June 1997) do not overlap with those from the current series of global ocean color instruments. Currently, the investigations of merger techniques for derived ocean color data products, particularly chlorophyll-*a*, center on four approaches (Gregg, 2001): a simple splicing and averaging of measurements from two or more satellite instruments; a subjective analysis, where specific deficiencies of individual sensors are identified and used to weight the results from the mergers; the application of the Conditional Relaxation and Analysis method used by Gregg and Conkright (2001) to merge CZCS satellite measurements with *in situ* results; and an optimal interpolation method designed to maintain continuity within the merged data set. Each approach has strengths and weaknesses, and each has been applied, in a preliminary manner, to measurement results from SeaWiFS and MODIS. Refinements of these analyses will continue as reprocessed, science-quality MODIS ocean color measurements become available in the second half of 2001.

In addition, the SIMBIOS Program is investigating the use of semi-analytical in-water algorithms as a basis for merging measurements from multiple satellite instruments (Siegel and Maritorena, 2000) . In this approach, the algorithm is adapted to convert the radiometric results from each ocean color instrument's measurements (water-leaving radiance or remote sensing reflectance) into the optical properties of the water (the coefficients for absorption and backscattering). And from these properties, the derived ocean color products, including chlorophyll-*a*, are derived. The use of a semi-analytical model allows the merger of the measurements at the level of the radiometric measurements, rather than at the level of the derived geophysical products. This approach gives a single, consistent method for deriving geophysical products from the radiometric measurements of the instruments. It can be adapted to individual satellite and *in situ* sensors, since it can be adapted for the different measurement wavelengths of different instruments. However, this approach also requires a single, consistent atmospheric correction algorithm and a single in-water bio-optical model.

Presently, we are unable to evaluate fully the relative advantages of these two basic merger techniques – merger at the level of the derived data products (the outputs of individual in-water algorithms from individual instruments) or merger at the level of the radiometric measurements (the inputs of individual instruments to a common in-water algorithm). The development of these merger techniques remains an active research area for the SIMBIOS Program.

5. Concluding Remarks

The SIMBIOS Program has solicited advice from the IOCCG on the merger of multi-platform ocean color measurements, including the spatial and temporal resolution of the derived data set. The IOCCG has been actively involved with the issues surrounding complementary ocean color missions (IOCCG, 1999). It is anticipated that a partnership between the IOCCG and the SIMBIOS Program will lead to a data set that meets the needs of the international ocean color community. However, the coordination of a long-term multi-platform ocean color data set by the SIMBIOS Program and the IOCCG is a scientific and technological experiment requiring collaboration by the international community. The SIMBIOS Program has developed a set of tools and procedures to initiate such a data set. However, we recognize that, along with its usefulness, there will be deficiencies in it. We anticipate that the improvements to this ocean color data set will come from collaborations with our colleagues within – and without of – the SIMBIOS Program. It is a work in progress.

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Table 1. An example of MOBY/MOCE vs MODIS match-up data for Julian day 345, 2000. Data collected during MOCE 7.

moce	21.447	-158.382	Mebsops	MODOCL2.A2000345.2135.002.2001042155702																						
row	column	latitude	longitude	nlw 412	nlw 443	nlw 488	nlw 531	nlw 551	nlw 667	nlw 678	quality	mirror	detector	sat z	sat a	sun z	sun a	Tau 865	eps 78	aer mod 1	aer mod 2	CZCS Tot	Tot Chla M	Tot Pig M	TSM	K(490)
547	860	21.458	-158.396	16.355	14.652	11.038	4.011	2.977	0.240	0.184	0	1	7	16.44	-260.62	46.11	163.84	0.094	0.978	2	3	0.122	0.089	0.211	0.089	0.037
548	860	21.449	-158.397	16.364	14.732	11.074	4.075	3.026	0.298	0.232	0	1	8	16.44	-260.30	46.10	163.83	0.101	0.971	2	3	0.124	0.091	0.219	0.090	0.037
549	860	21.439	-158.399	16.285	14.510	10.807	3.898	2.867	0.201	0.154	0	1	9	16.44	-259.98	46.10	163.83	0.095	0.986	4	5	0.116	0.084	0.197	0.085	0.036
547	861	21.456	-158.385	16.170	14.533	10.847	3.906	2.888	0.172	0.144	0	1	7	16.53	-260.61	46.11	163.85	0.087	0.981	3	4	0.117	0.085	0.200	0.086	0.036
548	861	21.447	-158.387	16.299	14.708	10.939	3.960	2.922	0.240	0.179	0	1	8	16.53	-260.30	46.10	163.85	0.092	0.979	3	4	0.117	0.085	0.201	0.086	0.036
549	861	21.438	-158.388	16.451	14.540	10.767	3.870	2.890	0.222	0.154	0	1	9	16.53	-259.98	46.09	163.84	0.093	0.985	4	5	0.117	0.085	0.202	0.086	0.037
547	862	21.454	-158.375	15.965	14.296	10.703	3.797	2.808	0.191	0.137	0	1	7	16.62	-260.61	46.10	163.86	0.110	0.988	4	5	0.115	0.083	0.193	0.085	0.036
548	862	21.445	-158.377	16.176	14.527	10.821	3.846	2.842	0.224	0.150	0	1	8	16.62	-260.29	46.10	163.86	0.083	0.982	3	4	0.114	0.082	0.191	0.084	0.036
549	862	21.436	-158.378	16.042	14.109	10.462	3.680	2.727	0.171	0.136	0	1	9	16.62	-259.98	46.09	163.85	0.114	0.996	5	7	0.112	0.080	0.186	0.083	0.036
		MODIS	average	16.234	14.512	10.829	3.894	2.883	0.218	0.163										MODIS	average	0.117	0.085	0.200	0.086	0.036
	MOS - FOS 600's	345	1	19.311	16.211	12.111	4.411	3.268	0.208	0.191									MOS - FOS 600's			0.120	0.088	0.209	0.088	0.037
	MOS RDF Corrected	345	2	19.118	16.103	11.969	4.382	3.246	0.000	0.000									MOS RDF Corrected			0.120	0.088	0.210	0.088	0.037
	MOS Stray adj	345	3	20.856	16.535	12.353	4.499	3.333	0.000	0.000									MOS Stray adj			0.120	0.088	0.209	0.088	0.037
	MOS Rads&Stray Adj	345	4	20.647	16.425	12.209	4.470	3.311	0.000	0.000									MOS Rads&Stray Adj			0.120	0.088	0.210	0.088	0.037
	% diff lnw-MODIS			15.933	10.481	10.588	11.728	11.781	-4.647	14.485									% diff lnw-MODIS			2.601	3.143	4.152	2.153	1.169
	% diff lnw(rdf)-MODIS			15.085	9.881	9.527	11.144	11.183	#DIV/0!	#DIV/0!									% diff lnw(rdf)-MODIS			2.589	3.128	4.746	2.143	1.602
	% diff lnw(stray)-MODIS			22.161	12.235	12.340	13.455	13.501	#DIV/0!	#DIV/0!									% diff lnw(stray)-MODIS			2.584	3.123	4.125	2.140	1.161
	% diff lnw(rdf+stray)-MODIS			21.373	11.648	11.306	12.893	12.927	#DIV/0!	#DIV/0!									% diff lnw(rdf+stray)-MODIS			2.593	3.134	4.747	2.147	1.600

MOBY	20.82	-157.185	Mebsops	MODOCL2.A2000345.2135.002.2001042155702																						
row	column	latitude	longitude	nlw 412	nlw 443	nlw 488	nlw 531	nlw 551	nlw 667	nlw 678	quality	mirror	detector	sat z	sat a	sun z	sun a	Tau 865	eps 78	aer mod 1	aer mod 2	CZCS Tot	Tot Chla M	Tot Pig M	TSM	K(490)
594	979	20.831	-157.199	17.645	14.805	10.914	3.964	2.909	0.211	0.167	0	0	4	27.34	-260.72	45.20	165.20	0.096	1.010	5	7	0.115	0.083	0.197	0.085	0.036
595	979	20.821	-157.200	17.661	14.903	10.965	4.094	3.024	0.238	0.190	0	0	5	27.34	-260.52	45.19	165.19	0.097	0.998	5	7	0.122	0.089	0.217	0.089	0.038
596	979	20.811	-157.202	17.734	14.776	10.938	3.988	2.951	0.220	0.191	0	0	6	27.34	-260.33	45.19	165.19	0.093	1.010	5	7	0.118	0.086	0.205	0.087	0.037
594	980	20.829	-157.187	17.373	14.694	10.960	4.040	2.984	0.244	0.196	0	0	4	27.43	-260.71	45.20	165.21	0.098	1.001	5	7	0.122	0.089	0.214	0.089	0.037
595	980	20.819	-157.189	17.446	14.756	10.965	4.100	3.035	0.220	0.174	0	0	5	27.43	-260.52	45.19	165.20	0.097	1.000	5	7	0.125	0.092	0.223	0.090	0.038
596	980	20.809	-157.190	17.668	14.797	10.930	4.061	2.994	0.240	0.181	0	0	6	27.43	-260.32	45.18	165.20	0.095	1.000	5	7	0.121	0.088	0.214	0.088	0.037
594	981	20.827	-157.175	17.108	14.490	10.892	4.052	2.979	0.236	0.191	0	0	4	27.52	-260.71	45.19	165.22	0.095	1.003	5	7	0.125	0.092	0.219	0.090	0.037
595	981	20.817	-157.177	17.180	14.690	10.851	4.130	3.071	0.224	0.205	0	0	5	27.52	-260.51	45.19	165.22	0.096	0.997	5	7	0.128	0.095	0.235	0.093	0.038
596	981	20.807	-157.179	17.681	14.869	10.951	4.142	3.045	0.246	0.213	0	0	6	27.52	-260.32	45.18	165.21	0.085	0.992	4	5	0.124	0.091	0.222	0.090	0.038
			average	17.500	14.753	10.930	4.063	2.999	0.231	0.190											average	0.122	0.089	0.216	0.089	0.037
		20h	moby	17.160	15.140	11.700	4.370	3.250	0.130	0.130										20h	moby	0.134	0.100	0.240	0.096	0.038
		22h	moby	18.050	15.870	12.220	4.580	3.410	0.140	0.130										22h	moby	0.134	0.100	0.241	0.096	0.038
		% diff moby20h-MODI		-1.979	2.554	6.585	7.015	7.720	-77.692	-45.983										% diff moby20h-MODIS		8.851	10.704	9.729	7.208	1.067
		% diff moby22h-MODI		3.050	7.036	10.560	11.279	12.050	-65.000	-45.983										% diff moby22h-MODIS		8.997	10.879	10.357	7.326	1.468