Overview of the Radiometric Calibration of MOBY

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ABSTRACT

The Marine Optical Buoy (MOBY) provides values of water-leaving radiance for the calibration and validation of satellite ocean color instruments. Located in clear, deep ocean waters near the Hawaiian Island of Lanai, MOBY measures the upwelling radiance and downwelling irradiance at three levels below the ocean surface plus the incident solar irradiance just above the surface. The radiance standards for MOBY are two integrating spheres with calibrations based on standards traceable to the National Institute of Standards and Technology (NIST). For irradiance, the MOBY project uses standard lamps that are routinely recalibrated at NIST. Wavelength calibrations are conducted with a series of emission lines observed from a set of low pressure lamps. Each MOBY instrument views these standards before and after its deployment to provide system responses (calibration coefficients). During each deployment, the stability of the MOBY spectrographs and internal optics are monitored using three internal reference sources. In addition, the collection optics for the instrument are cleaned and checked on a monthly basis while the buoy is deployed. Divers place lamps over the optics before and after each cleaning to monitor changes at the system level. As a hyperspectral instrument, MOBY uses absorption lines in the solar spectrum to monitor its wavelength stability. When logistically feasible during each deployment, coincident measurements are made with the predecessor buoy before that buoy's recovery. Measurements of the underwater light fields from the deployment vessel are also compared with those from the buoy. Based on this set of absolute calibrations and the suite of stability reference measurements, a calibration history is created for each buoy. These calibration histories link the measurement time series from the set of MOBY buoys. In general, the differences between the pre- and post-deployment radiance calibrations of the buoys range from +1% to -6% with a definitive bias to a negative difference for the post-deployment values. This trend is to be expected after a deployment of 3 months. To date, only the pre-deployment calibration measurements have been used to adjust the system responses for the MOBY time series. Based on these results, the estimated radiometric uncertainty for MOBY in-water ocean color measurements is estimated to be about 4% to 8% (k=1). As part of a collaboration with NIST, annual radiometric comparisons are made at the MOBY calibration facility. NIST personnel use transfer radiometers and integrating spheres to validate (verify) the accuracy of the MOBY calibration sources. Recently, we began a study of the stray light contribution to the radiometric uncertainty in the MOBY systems. A complete reprocessing of the MOBY data set, including the changes within each MOBY deployment, will commence upon the completion of the stray light characterization, which is scheduled for the fall of 2001. It is anticipated that this reprocessing will reduce the overall radiometric uncertainty to less than 5% (k=1).

Keywords: MOBY, Marine Optical Buoy, ocean color, calibration

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Earth Observing Systems VI, William L. Barnes, Editor,
Proceedings of SPIE Vol. 4483 (2002) © 2002 SPIE · 0277-786X/02/$15.00

Table 1. MOBY deployment history.

MOBY Number	Deployment Date	Recovery Date	Comments
1	15 Sep 1996	3 Nov 1996	
2	16 Nov 1996	1 Mar 1997	all data suspect – optical multiplexer misalignment
3	20 Jul 1997	8 Dec 1997	MOBY adrift – 27 Oct 1997 to 30 Oct 1997 MOBY adrift – 30 Nov 1997 to 8 Dec 1997
4	1 Dec 1997	23 Apr 1998	
5	21 Apr 1998	25 Jul 1998	top arm gone, no data from arm – 18 May 1998
6	24 Jul 1998	27 Oct 1998	
7	24 Oct 1998	7 Feb 1999	
8	9 Feb 1999	3 May 1999	
9	1 May 1999	31 July 1999	Data disk malfunction, last data from buoy – 25 Jul 1999
10	29 Jul 1999	18 Nov 1999	
11	15 Nov 1999	10 Feb 2000	top arm broken, no data from arm – 22 Nov 1999
12	13 Feb 2000	16 May 2000	
13	15 May 2000	5 Aug 2000	
14	3 Aug 2000	4 Dec 2000	
15	3 Dec 2000	1 Mar 2001	top arm broken, no data from arm – 9 Jan 2001
16	1 Mar 2001	1 Jun 2001	
17	1 Jun 2001	present	

1. INTRODUCTION

The operational versions of the MOBY buoy were deployed for testing in September 1996 (MOBY-1) and November 1996 (MOBY-2). Since then, a series of buoys has been deployed, giving a nearly continuous time series of ocean measurements for the last five years (Table 1). The current MOBY (MOBY-17) was deployed in June 2001. It is expected to be replaced in September 2001. The MOBY measurements overlap the measurement time series from several satellite-borne ocean color sensors. The previous ocean color missions of the Ocean Color and Temperature Scanner (OCTS) and the Polarization and Directionality of the Earth's Reflectances (POLDER), both onboard ADEOS-I, extended from November 1996 to June 1997. Current ocean color satellite instruments include the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), launched on OrbView-2 in August 1997, and the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multiangle Imaging Spectroradiometer (MISR), launched on Terra in December 1999. For the previous and current ocean color instruments, MOBY has provided water-leaving radiances as calibration and validation references. Future ocean color missions (within the next two years) include MODIS on Aqua, the Medium Resolution Imaging Spectroradiometer (MERIS) onboard Envisat, and the Global Imager (GLI) and POLDER-II on ADEOS-II. It is anticipated that MOBY will continue to provide water-leaving radiances for these missions as well.

The calibration plans for these satellite instruments include their prelaunch characterization and calibration, plus a variety of onboard measurements – including those of internal lamps, of the sun (using onboard diffuse reflecting plaques), and of the moon – to monitor instrument changes. However, with the review of the Coastal Zone Color Scanner (CZCS) calibration by Evans and Gordon[1], it has become clear that onboard calibration techniques alone are inadequate to provide good ocean color measurements. In principle, this is due to the nature of the satellite measurements. For ocean measurements from space, the majority of the light flux at the top-of-the-atmosphere (90% or more) comes from the atmosphere. For blue ocean waters, the atmospheric contribution is about 90% at 410 nm (in the blue), 96% at 550 nm (in the green), and 99.5% at 670 nm (in the red). Since the removal of the atmospheric radiance is an essential part of ocean color measurements[2], the radiance from the ocean is calculated as the small difference between two large values. Consequently, an error of 1% in the top-of-the-atmosphere radiance can cause an error of 10% or more in the derived radiance for the blue bands at the ocean surface. As a result, several ocean color sensors, including SeaWiFS and MODIS, are vicariously calibrated instruments. Here, the term vicarious has the definition – "as seen through the eyes of another." The primary surface "truth" reference for the vicarious calibration of these instruments is MOBY.

2. THE MARINE OPTICAL BUOY (MOBY)

The MOBY site is located in 1200 m of water approximately 18 km from the west coast of the Hawaiian Island of Lanai (Fig. 1). The mountains on the islands of Molokai, Lanai, and Maui provide a lee from the dominant trade winds, reducing the sea

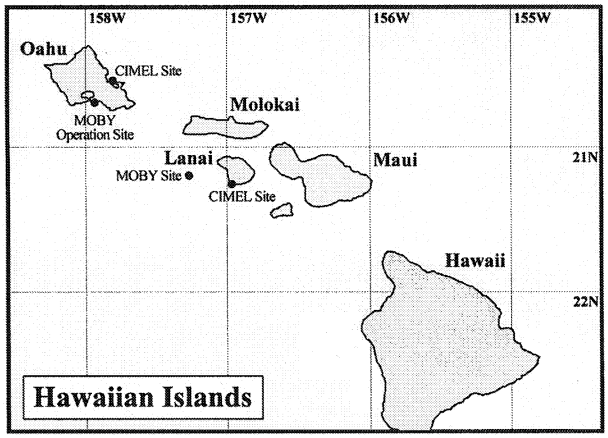

Figure 1. Chart of the MOBY site. The site is in the lee of the islands of Lanai, Maui, and Molokai.

swell and cloud cover at the site. The MOBY operations site is located in Honolulu, on the south shore of the island of Oahu, at the University of Hawaii's Marine Center on pier 45. The MOBY project also operates Cimel* sun photometers for the Aerosol Robotic Network (AERONET) Project on the southwest shore of Lanai and on the eastern shore of Oahu to provide auxiliary atmospheric measurements. Finally, there are cellular telephone relay sites on Lanai, Maui, and Molokai to provide communications between the buoy and the operation site.

MOBY is a wave-rider buoy tethered to a slack-line moored buoy to prevent drifting. This arrangement keeps MOBY oriented as a vertical column extending from the ocean surface to a depth of 12 m at the buoy's base (Fig. 2). The surface float for the buoy is 1.7 m in diameter with four 40 W solar panels mounted to the antenna support column. The float houses the controlling computers, data storage, electronics, cellular modem, global positioning system receiver, and computer battery. The Marine Optical System (MOS) is located in the instrument bay at the base of the buoy, along with four 200 A/h marine batteries. The upwelling radiances (L_u's) and downwelling irradiances (E_d's) within the ocean are measured by remote collectors positioned on arms away from the buoy's central column. The arms can be positioned along the column at varying depths, typically 1.5 m, 5 m, and 9 m. The incident solar irradiance (E_s) is measured at the top of the surface float. The remote collectors are connected to 1 mm, ultraviolet-transmitting, silica fiber-optic cables that are terminated at a fiber-optic rotary selector (multiplexer). This optical multiplexer is mounted on one of the entrance windows of the MOS spectrograph, and light is transmitted into the MOS optical train, through the spectrographs, and then onto the thermoelectrically cooled detectors. The optical and ancillary data from MOS are relayed to the surface computer and stored on disk for access via a cellular telephone link.

3. WATER-LEAVING RADIANCE AT NADIR

MOBY makes measurements at three depths near the ocean surface. The shallowest measurements (at 1.5 m) are propagated upward to just below the ocean surface by calculating the upwelled spectral radiance coefficient $K_L(\lambda)$ using

$$K_L(\lambda) = \frac{1}{z_2 - z_1} \ln\left[\frac{L_u(z_1,\lambda)}{E_s^{t_1}(\lambda)} \frac{E_s^{t_2}(\lambda)}{L_u(z_2,\lambda)} \right] \tag{1}$$

where λ is the wavelength and z_1 and z_2 are the two shallowest depths at which measurements are made ($z_1<z_2$). The solar irradiances E_s^{t1} and E_s^{t2} are the averages of the E_s measurements before and after the in-water L_u measurements to remove the effects of solar irradiance changes from those measurements[3]. The convention for this calculation is that the depth at the surface is zero and that the values of z increase with depth. Then the radiance change between depth z_1 and the surface is calculated using

$$L_u(0,\lambda) = L_u(z_1,\lambda)\exp\left[K_L(\lambda)z_1\right]. \tag{2}$$

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*Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

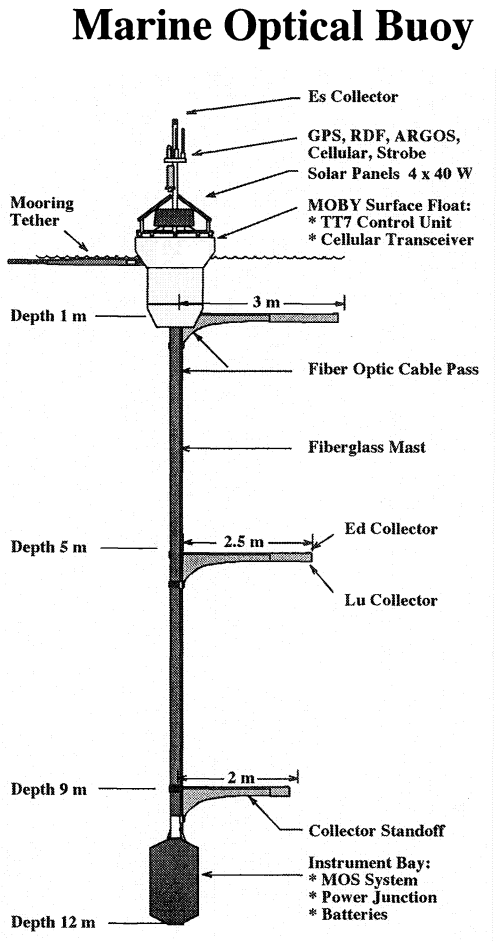

Figure 2. Schematic of the Marine Optical Buoy (MOBY).

The propagation of the upwelling radiance through the ocean surface, that is, the calculation of the water-leaving radiance, is accomplished using

$$L_w(0,\lambda) = \frac{T_F}{n^2} L_u(0,\lambda), \tag{3}$$

where $L_w(0,\lambda)$ is the water-leaving radiance, n is the index of refraction of water, and T_F is the Fresnel transmittance of the air-sea interface[3]. The time-averaged value of T_F for the ocean surface, as a function of wind speed at the surface, has been given by Austin[4]. These calculations assume the transmission of light along a vertical path through the ocean and the ocean surface, providing the spectral radiance for a nadir-viewing instrument immediately above the ocean surface. In practice, these calculations are complicated by the angular dependence of the upwelling radiance, the water-leaving radiance, and the Fresnel transmittance, given in terms of the polar and azimuthal angles in polar coordinates[3]. Finally, for comparisons with satellite-borne ocean color instruments, the high-resolution water-leaving radiance spectra from MOBY are convolved with the spectral responses of the satellite bands to form band-averaged spectral radiances[5].

For MOBY measurements, the propagation of light to the surface is made from the topmost arm of the buoy (z_l=1.5 m). However, as shown in Table 1, there are periods when the topmost arm is either broken or missing. For these periods, the center arm (z_l=5 m) is used in its place.

4. THE MARINE OPTICAL SYSTEM (MOS)

There are four Marine Optical Systems in the MOBY program – one in the deployed buoy, one in the buoy undergoing refurbishment, one in the Profiler, and one as a spare. The Profiler is a shipboard version that provides observations of the apparent optical properties of the ocean (L_u's and E_d's) during MOBY deployment cruises and during other validation cruises for satellite

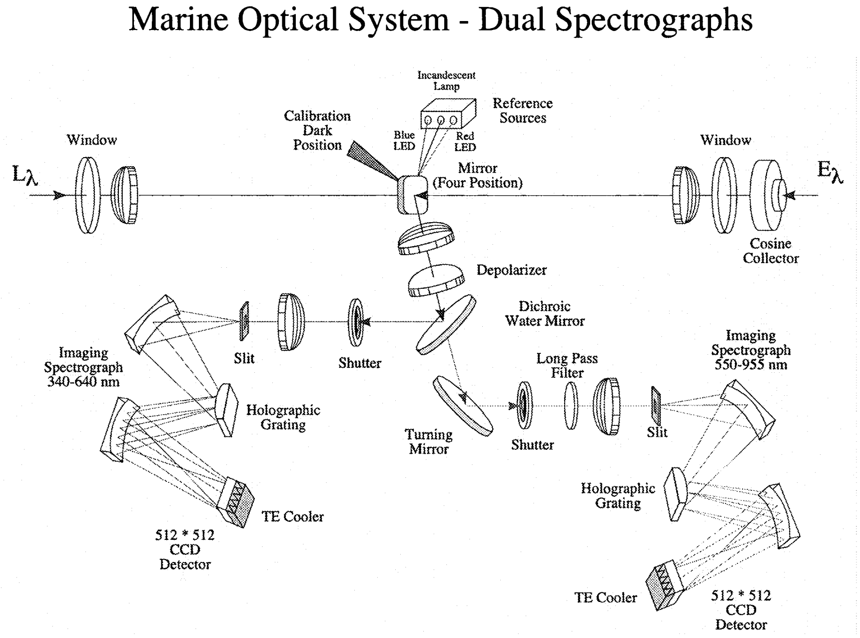

Figure 3. Schematic of the optical train of the Marine Optical System (MOS). Light from the radiance and irradiance collectors enter the spectrograph through the four position mirror. On command, the mirror allows light from the calibration sources to enter MOS – or allows the instrument to view a dark target to set the zero offset. The blue spectrograph measures from 340 nm to 640 nm using a 512x512 CCD array. The red spectrograph measures from 550 nm to 955 nm, also with a 512x512 array.

ocean color instruments. The schematic for the Profiler and its Marine Optical System (MOS) is shown in Fig. 3. It includes one E_d collector and one L_u collector. The MOS system contains two spectrographs, one to measure light in the near ultraviolet and visible from 340 nm to 640 nm (the blue spectrograph), and one to measure light in the red and near infrared from 550 nm to 955 nm (the red spectrograph).

The basic optical design for the collection optics allows the measurement of the input radiance at a small angular field of view through an ultraviolet-transmitting silica viewing window. In order to measure irradiance, a cosine collector is attached over the viewing port, allowing the diffuse light exiting the back side of the cosine collector to be measured, as illustrated in Fig. 3. This allows the MOS spectrographs to handle light from the two types of collectors in the same manner. For the MOBY buoy, a set of collection optics for E_s, E_d, and L_u (see Fig. 2) was designed to be coupled through multi-mode fiber optic cables. Light from each of these collectors on the buoy is relayed to the MOS spectrographs through an optical multiplexer which physically replaces the irradiance collector that is illustrated in Fig. 3. Operating under computer control, up to 10 multiplexer ports can be selected. Also under computer control, a four position mirror within MOS allows, on command, light from the windows, multiplexer, or from the calibration sources to impinge on the detectors. A dark target position is available to set the zero offset; however, in the operational versions, this function is accomplished with shutters. In addition, the depolarizer optic is not used in the configuration for the MOBY systems.

In consideration of the large range of values present in the spectral composition of water, due to its absorption properties, a dichroic mirror was designed for MOS to reduce the potential for stray light contamination of the observations. This dichroic mirror (see Fig. 3) spectrally separates the input radiance, reflecting the blue and green portion into the blue spectrograph and transmitting the red and near infrared portion into the red spectrograph. For the dichroic, the reflectance is nearly 100% for wavelengths from 400 nm to 600 nm, and the transmittance averages 90% for wavelengths between 700 nm and 1000 nm. There is a transition in the wavelength region between 600 nm and 700 nm. In this region, the reflectance of the dichroic decreases with wavelength and the transmittance increases with wavelength. This transition can be seen in the radiance responsivity curves for the two spectrographs in Fig. 4. The responsivities are given as the outputs of each channel of the spectrograph (with units of counts per second) per unit radiance (with units of $\mu W\ cm^{-2}\ sr^{-1}\ nm^{-1}$). These are nominal responsivity spectra for the spectrographs taken from one of the pre-deployment calibrations at the MOBY operations facility. Actual responsivities

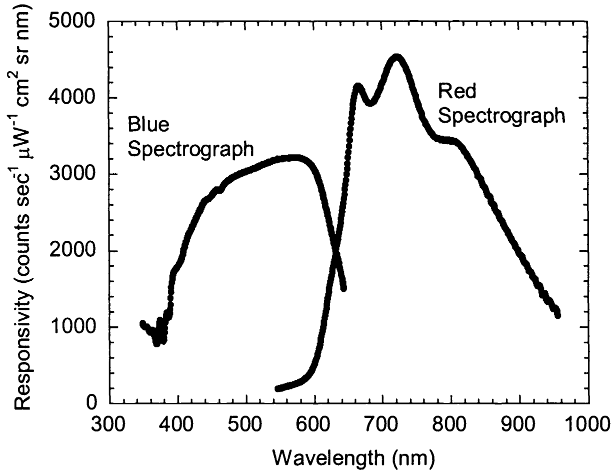

Figure 4. Radiance responsivities of the blue and red spectrographs in the MOS. The responsivities are given as the instrument output (in counts per second) per unit of input radiance.

vary from spectrograph to spectrograph and from calibration to calibration. However, Fig. 4 does show the general shapes of the radiance responsivities of the two spectrographs with wavelength. The reflectance and transmittance properties of the dichroic dominate these shapes, although other factors, such as the wavelength dependence of the quantum efficiency of the detector array, are important.

The spectrographs for MOS are based on the Offner design and reconfigured with original holographic convex diffraction gratings by American Holographic, Inc.* The CCD arrays in the spectrographs are thermoelectrically cooled to –38°C to stabilize the MOS outputs and to improve the signal-to-noise ratios in the measurements.

For the blue spectrograph, a holographic grating, operating in first order, separates the input light into its spectral components, and a two-dimensional CCD array collects this spectrum in 512 channels at wavelengths from 340 nm to 640 nm. For the red spectrograph, the array collects the spectrum in 512 channels for wavelengths from 550 nm to 955 nm. In addition, the optical path for the red spectrograph contains a long pass filter that blocks light at wavelengths shorter than about 600 nm. Along with the dichroic, this filter ensures that there is no second order diffracted light from the grating for wavelengths in the blue and green to contaminate the red spectrograph's measurements in the red and near infrared.

For the red spectrograph, the input radiance to the grating is small for wavelengths below 650 nm, since the transmittance of the dichroic is low. This leads to a significant contamination of the measurements at these wavelengths by light scattered through the spectrograph from longer wavelengths. When referring to filter radiometers, this scattered light is also called spectral out-of-band. The effect derives primarily from the diffraction characteristics of the spectrograph's single grating. Similar to the reflectance properties of a surface, light diffracted by the grating can be separated into three components: a specular component, a haze component, and a diffuse component. The proper separation of light by the spectrograph relies on the specular component only. The haze and diffuse components are stray light. A nominal function demonstrating the response of the MOS bench unit red spectrograph to monochromatic light at 747 nm[6] is shown in Fig. 5. The sharp central peak in the figure shows the specular component of the light diffracted from the grating. From about 650 nm to 850 nm, there is the presence of a haze from forward scattered light at angles near the scattering angle. This haze decreases with angle away from the diffraction direction, and the detectors near the peak – with angles near the scattering angle – receive more of the haze component. At all angles, there is a background of diffusely scattered light from the grating that is nearly constant with angle – contaminating all detectors equally. The response function is the combined sum of the three components. For the blue spectrograph, the response function has a similar shape. The effect of stray light can be reduced using an instrument with two gratings or with a grating combined with a prism.

In operation, the MOS spectrographs do not view monochromatic light. For each channel, the detector receives the specular reflectance from the grating for its own wavelength, plus the haze from nearby wavelengths, plus the diffuse contribution. For transition regions of the dichroic, such as the region below 650 nm in the MOS red spectrograph, the specular component of the

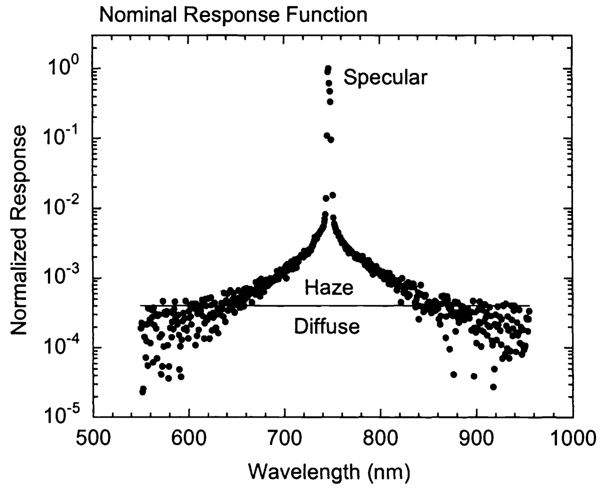

Figure 5. A response function for the MOS bench unit red spectrograph. The figure shows the response to monochromatic light with a wavelength near 745 nm. The sharp central peak shows the specular reflectance from the grating at the grating's scattering angle for the input light. For the region with wavelengths within about 100 nm of the central peak, there is a haze of imperfectly reflected light at approximately the same scattering angle as the specular reflectance, a haze that decreases with distance away from the scattering angle. For all wavelengths, there is a background of nearly constant diffuse scattered light from the grating. The slit scattering function is the sum of the contributions from these three sources. The response functions for the MOS blue spectrograph have shapes similar to this.

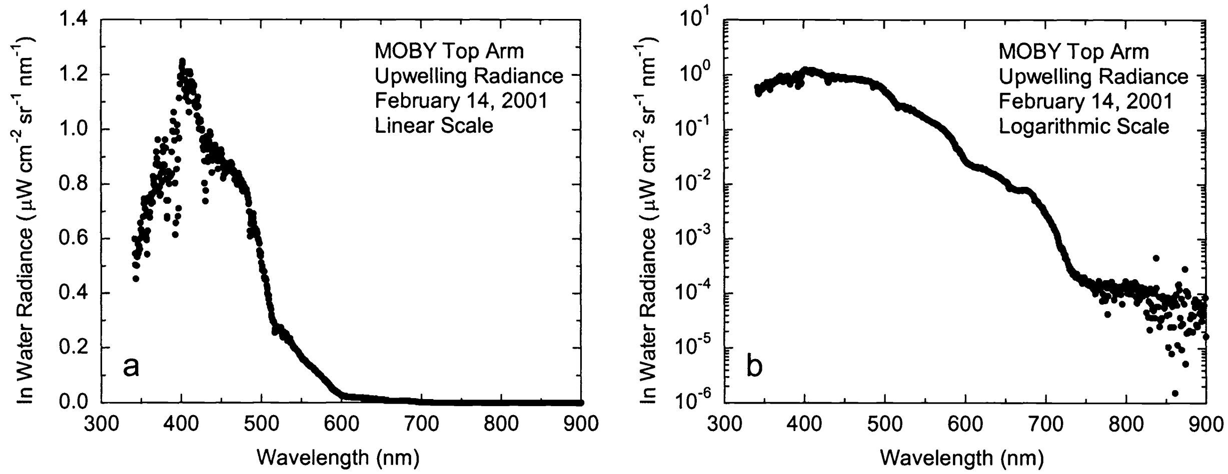

Figure 6. In-water measurement results from MOBY. The measurements of upwelling radiance were made on 14 February 2001 using the topmost MOBY arm. The measurements from the blue and red spectrographs are joined at 622 nm. Measurements at wavelengths greater than 900 nm are not shown. Both panels show the same measurement results.

a. Radiances on a linear scale.

b. Radiances on a logarithmic scale.

light incident onto a channel can be very low, so that the diffuse component and the haze from longer wavelengths can contribute a significant portion of the total signal. The amount of stray light contamination at a particular wavelength also depends on the spectral distribution of the source being measured and affects both the calibration and subsequent field measurements. The combined error in measuring an unknown source's radiance is minimized if the field source has the same spectral shape as the calibration source. In this case, the effect of the "excess light" nearly cancels. MOS is calibrated in the laboratory using lamp-illuminated integrating spheres where the flux peaks at wavelengths near 1000 nm. However, the MOBY buoy operates in clear ocean waters where the spectral radiance peaks near 400 nm. A typical ocean measurement result is shown in Fig. 6. Here the MOS spectrographs measure the radiance from the MOBY top-arm radiance collector. Figure 6b shows that radiances beyond 650 nm are small, but finite; there is still a pattern and structure to the measurement results. This is due to the excellent dynamic

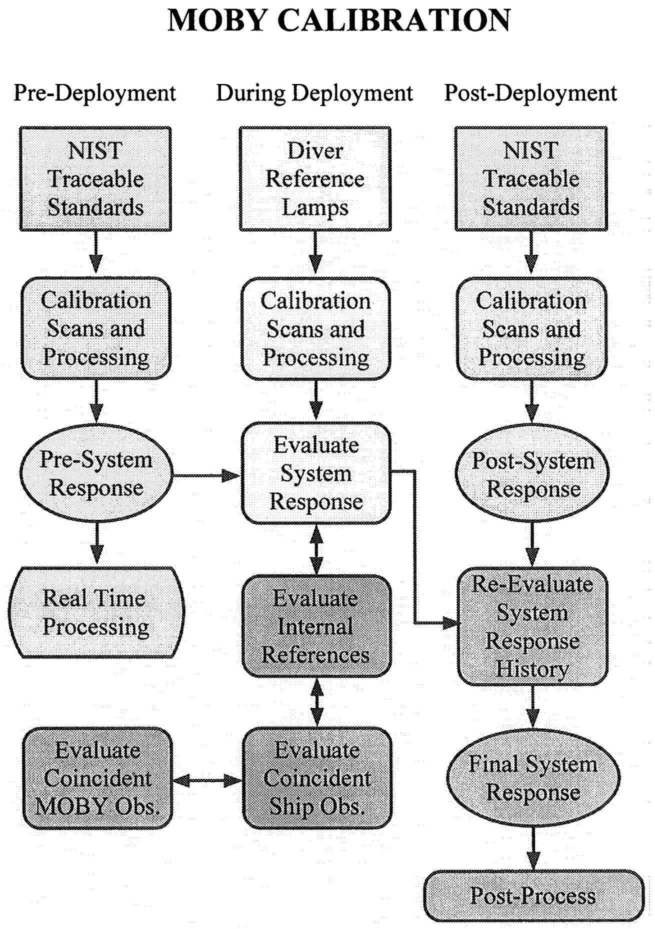

Figure 7. Calibration Flowchart for MOBY Measurements.

range (up to 10^8) for the MOBY measurements, which results from variable CCD bin factors, variable integration times for the measurements, and detector cooling. In this case, the spectral out-of-band contributes significantly less "excess light" to the ocean measurement than to the calibration. This difference in "excess light" leads to radiance determinations from the red MOS spectrograph that are too low for wavelengths below 650 nm[6].

To account for stray light, the spectral responses of the MOS spectrographs in the MOS Profiler have been determined using a set of tunable lasers[7,8]. This approach enables the spectrographs' responsivities to be determined **with no stray light**. The laser wavelength was varied over the spectral ranges of the spectrographs, providing a complete set of slit scattering functions. These results were used to develop a stray light correction algorithm for MOS[8]. Each in-water radiance requires two measurements: a calibration measurement at the MOBY operations facility and a measurement in the water. Since the light in each measurement has its own spectral shape, each in-water radiance requires two correction factors. The correction factor for the laboratory measurement is fixed by the spectral shape of the integrating sphere's radiance; however, the spectral shape of the in-water measurements changes, depending on the chlorophyll concentration and the depth of the measurement, among other factors. The in-water measurements provide an initial spectrum for an iterative stray light correction.

Preliminary results from the NIST characterization of the MOS Profiler indicate that, in clear, blue waters, the measured values for light flux in the ocean are about 5% to 6% too low at 412 nm, about 3% too low at 443 nm, and about 2% to 3% too high at 555 nm, due to stray light effects in the MOS system. It must be stressed that these are preliminary results for the MOS Profiler and that the MOS systems in the MOBY buoys may give different results. Each MOS will require its own stray light correction factors, and these factors must be applied to the source spectral shape for each in-water measurement. However, the preliminary results presented here do provide a magnitude estimate of the stray light effects that must be accounted for.

5. MOBY ABSOLUTE CALIBRATION AND STABILITY TIME SERIES

To date, the MOBY time series includes 17 buoy deployments. The MOBY calibration program has three primary objectives. The first is to obtain absolute values in SI units that are directly traceable to NIST primary standards. The second is to link the calibrations of the individual buoys. To do this, the MOS system from each buoy is calibrated before and after deployment using irradiance and radiance standards that are, themselves, calibrated and monitored on a routine basis. This is a system calibration that includes the collecting optics and fiber optic cables in the buoy. The third objective is the monitoring of changes in the MOBY measurements during each deployment to provide a link between the calibrations performed pre- and post-deployment. Several times during each deployment, divers place lamps over the radiance and irradiance collectors at the end of each of the buoy's arms. These measurements check the response of the MOBY system from end-to-end. In addition, the spectrograph routinely views internal references (a white lamp and red and blue light emitting diodes) to check for changes within the spectrographs. These procedures are complemented by auxiliary comparison measurements, including coincident measurements from ships and from temporally overlapping MOBY buoys. The latter comparison is made during the interval between the deployment of the new buoy and the recovery of the old one. A flowchart for this process is given in Fig. 7. Once the set of measurements from before, during, and after the deployment is completed, a re-evaluation of the instrument's calibration history is performed. A complete reprocessing of the MOBY data set will commence upon the completion of the stray light characterization by NIST, which is scheduled for the fall of 2001.

5.1 INTEGRATING SPHERES AND STANDARD LAMP MONITORS (SLMs)

The radiance reference sources for the MOBY Program are two commercial integrating spheres, Optronic Laboratories models OL420 and OL425. Both spheres are routinely calibrated by the manufacturer, after about 50 hours of use. Upon arrival there, each sphere is calibrated against a NIST-traceable source. Then, the sphere is relamped and refurbished as necessary. Finally, the sphere is calibrated again before it is returned to the MOBY facility in Hawaii. As a result, the program has "before and after" calibrations of the spheres for each period of use. The OL420 sphere has been in use since 1992, well before the start of the MOBY time series. The OL425 sphere has been in use since August 1997. The uncertainty of the calibrations of the spheres is estimated to be 2.5% (k=1).

The irradiance references for the MOBY Program are a set of FEL irradiance lamps[9]. These are NIST primary standards that are routinely calibrated by NIST, after about 50 hours of use. The wavelength references are the emission lines from a set of mercury, argon, and neon low pressure lamps.

In addition, the MOBY Program has contracted NIST to build and calibrate two single-channel narrow-band filter radiometers, the Standard Lamp Monitors (SLMs). The SLMs were designed as simplified versions of the SeaWiFS Transfer Radiometer (SXR), also built by NIST[10]. In addition, each SLM has a transmission diffuser that can be used in place of the radiance fore optics. This allows each SLM to monitor both radiance and irradiance sources. The short wavelength SLM (SLM412) has a center wavelength at 411.8 nm and a bandwidth of 10.7 nm. The long wavelength SLM (SLM872) has a center wavelength at 872.2 nm and a bandwidth of 12.3 nm. For radiance measurements, the SLMs have 5° fields of view. For irradiance measurements, they view the full hemisphere in front of their collection optics in the same manner as the MOBY irradiance collectors . The SLMs are temperature stabilized at 28°C. They are routinely recalibrated at NIST, and the uncertainty of their radiance and irradiance calibrations is estimated to be 1.5% (k=1).

5.2 LONG-TERM CALIBRATION TIME SERIES

The measurements of the output of the OL420 integrating sphere by the SLM412 are shown in Fig. 8a. For these measurements, the sphere was operated using the lamp configuration from the manufacturer's calibration. The corresponding measurements by the SLM872 are shown in Fig. 8b. These panels also show the time series for the corresponding spectral radiances from the sphere. These time series extend from 23 May 1996 to the present. The sphere values in Fig. 8 are band-averages, using the spectral radiances from the sphere calibration curves and the relative spectral responses of the SLM channels:

$$L_B = \frac{\int_{\lambda_1}^{\lambda_2} L_\lambda R_\lambda d\lambda}{\int_{\lambda_1}^{\lambda_2} R_\lambda d\lambda}, \qquad (4)$$

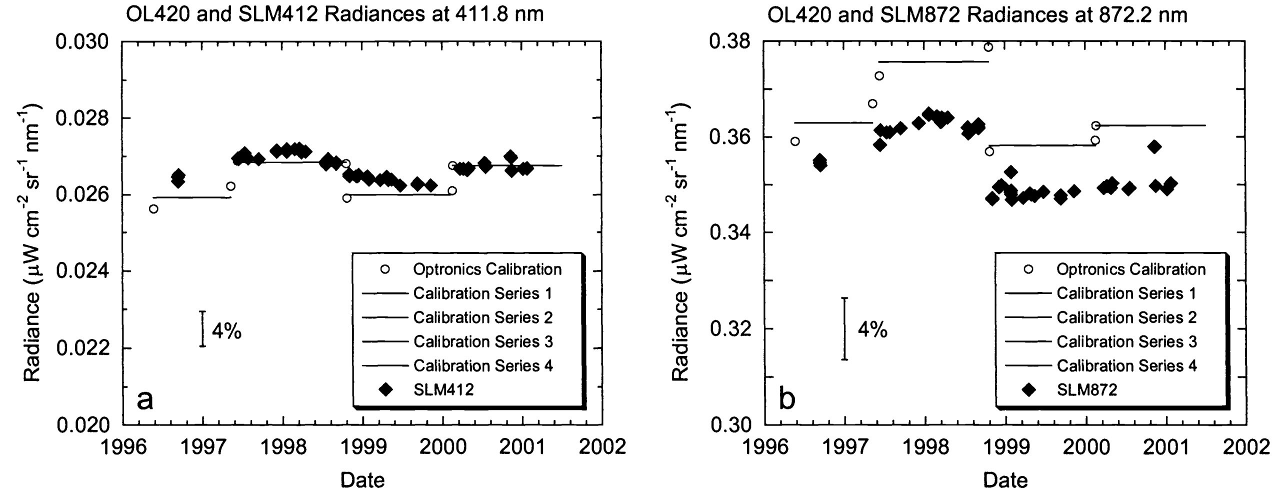

Figure 8. Time series of band averaged spectral radiances for the OL420 sphere and the SLMs. The open circles give the manufacturer's calibration values and the horizontal lines give the calibration time series for the sphere. The four calibration series cover the MOBY deployment history in Table 1. For calibration series 1 through 3, the horizontal line is the average of the manufacturer's calibrations occurring immediately before and after the series. For calibration series 4 there is, as yet, no calibration after the series.

a. OL420 and SLM412 radiances at 411.8 nm.

b. OL420 and SLM872 radiances at 872.2 nm.

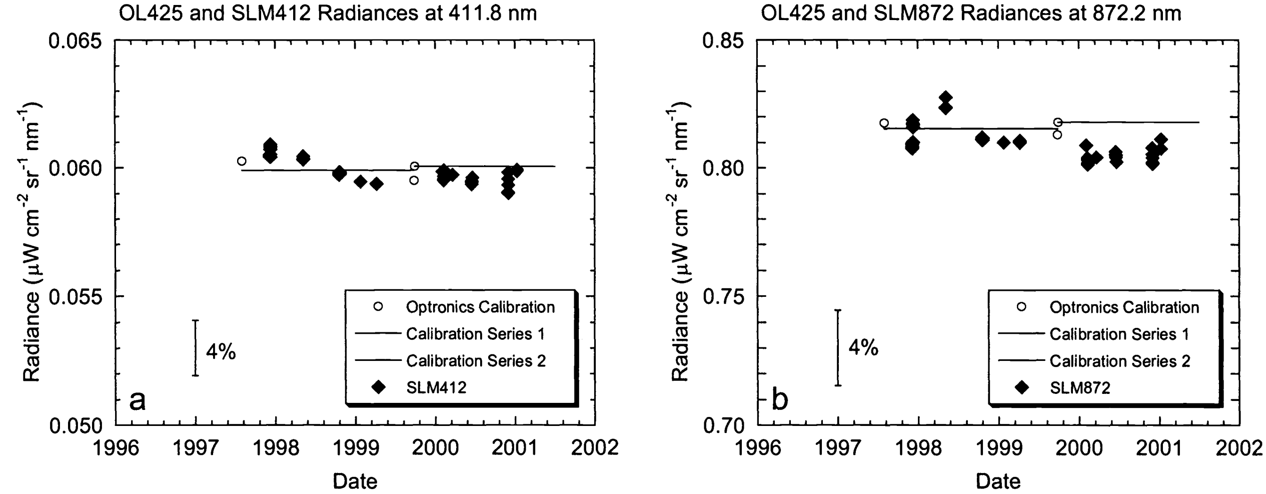

Figure 9. Time series of band averaged spectral radiances for the OL425 sphere and the SLMs. The format of this figure is the same as Figure 8, except for the integrating sphere.

a. OL425 and SLM412 radiances at 411.8 nm.

b. OL425 and SLM872 radiances at 872.2 nm.

where L_B is the band-averaged spectral radiance, L_λ is the spectral radiance from the source at wavelength λ, R_λ is the spectral response of the SLM, and λ_1 and λ_2 are the lower and upper wavelength limits for the integration – which are given by the wavelength range over which the SLM has a significant response. The units for the spectral radiances and the band-averaged spectral radiances are μW cm^{-2} sr^{-1} nm^{-1}.

The horizontal lines in Fig. 8 give the sphere spectral radiances for the periods between the "before" and "after" calibrations by the manufacturer. Since the SLMs show no significant drift in the outputs of the sphere over time, the lines between the Optronic calibration of the sphere are horizontal, giving the average of the "before" and "after" calibrations. This practice is the same for each calibration series (calibration time line), except for the current calibration series, which, as yet, has no "after" calibration by the manufacturer. The current series uses the "before" calibration, only – and assumes no drift in the sphere output since that calibration. The horizontal lines give the calculated values for the band-averaged spectral radiances that the SLMs "should" see, based on the manufacturer's calibration of the sphere.

Both the calibration of the sphere and the calibration of the SLMs are traceable to NIST, albeit with different paths. However, measured values by the SLMs are not the same as those calculated from the manufacturer's calibration of the sphere. On the average, the OL420 values for the SLM412 average 1.2% lower than the SLM measured values. For the SLM872, the OL420 values are 4.4% higher. At 412 nm the differences between the two calibrations are well within the combined uncertainties of the two calibrations (OL420: 2.5%, k=1; SLM: 1.5%, k=1). At 872 nm, the differences are outside of the combined uncertainties for k=1 but within the uncertainties for k=2. At present, the Optronic calibration is used to set the calibration coefficients for the MOS spectrographs, and the SLM measurements are used to validate (verify) the manufacturer's calibration.

A similar comparison of the radiances from the OL425 sphere and the SLMs is shown in Fig. 9. For this sphere, the differences between the calculated and measured values are less than 1%. The time series for the OL425 starts on 31 July 1997 and continues into the present.

Before and after each deployment, the MOS spectrograph views the integrating spheres through the MOBY fiber optics and collecting optics to give the system responses (see Fig. 7). In addition, several procedural approaches to incorporate the results from the NIST comparison measurements at the MOBY operations site into the MOBY calibration time series are under evaluation. However, the pre- and post-deployment calibrations do not provide the time dependence for the instrument changes during the deployment. And in general, the differences between the pre- and post-deployment calibrations of the buoys range from 1% to 6%.

5.3 CALIBRATION CHANGES DURING DEPLOYMENTS

During each deployment, the MOS spectrographs observe three internal light sources, an incandescent lamp and two light emitting diodes, one blue and one red. During each of its measurement cycles, they provide three time series for the changes in the spectrograph's response. Of course, from these measurements, it is not possible to separate changes in the spectrograph from changes in the internal light sources, themselves. However, the values for the pre- and post-deployment system responses (calibration coefficients) fix the magnitude of the system change, so the lamp measurements allow an evaluation of the uniformity of the rate of change during the deployment. Measurements of the reference sources show the MOS spectrograph outputs to be stable at the 1% level over the period of each MOBY deployment.

The change in the response of the MOBY system includes more than the change in response of the spectrograph, itself. In particular, the cosine bezels provide attachment surfaces for ocean animals, such as gooseneck barnacles, and as a result, these optics are prone to biological fouling. The radiance collectors are protected, for the most part, by anti-fouling tubes which use copper surfaces and a slow release of bromide. Divers visit the buoy on a monthly basis to clean the collection optics and to replace the anti-fouling devices. In addition, the divers document the condition of the buoy and its optics using underwater photography. Before and after each cleaning, the diver places a lamp over each collection optic to obtain a measure of the change in the transmission efficiency of the optic between cleanings. This commercial, underwater lamp has been modified with the addition of constant current circuitry to its battery pack and with the construction of lamp housings that fit over the MOBY irradiance and radiance collectors. These housings block ambient light and maintain a fixed distance between the collectors and the lamp. Laboratory tests of the lamp systems indicate that the systems are repeatable at the 1% level so long as the battery packs remain within one-quarter of full charge. The results of a set of pre- and post-cleaning measurements is shown in Fig. 10. An evaluation of the instrument changes from the internal references and from the external lamp measurements provides the overall time dependence of the instrument output during each deployment. The measurements of the internal sources have remained stable during each MOBY deployment, changing by 1% or less. For the measurements using the divers lamps, changes to the in-water time series are made when the pre- and post-cleaning measurements differ by more than 4%, which is the estimated uncertainty for each of these measurements.

5.4 WAVELENGTH CHANGES DURING DEPLOYMENTS

Since MOS is a hyperspectral instrument, the structure in the downwelling irradiance is present in the MOBY data set. This line structure comes from the absorption of energy in the Sun's atmosphere (Fraunhofer lines) and in the Earth's atmosphere (oxygen A-band absorption near 762 nm). The wavelengths of these absorption features are known and provide a reference to monitor wavelength drifts in the spectrographs. During the 17 MOBY deployments, there have been no signs of wavelength changes, within the wavelength resolutions of the spectrographs.

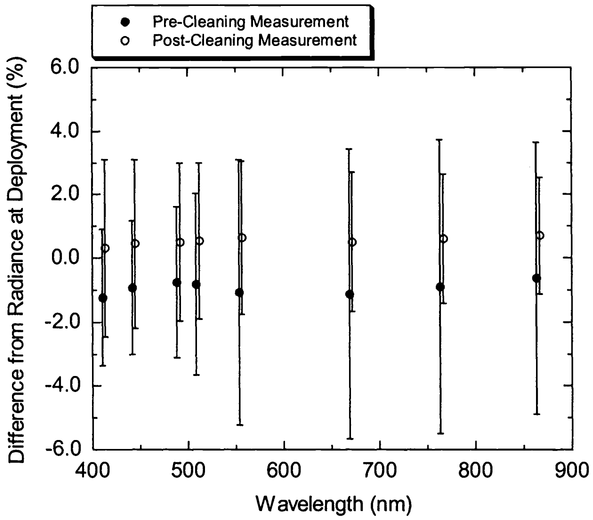

Figure 10. Pre- and Post-Cleaning Measurements of the MOBY Top Arm Radiance Collector on 4 October 2000. The measurement results are given as the are differences from the lamp measurements on the day of the buoy's deployment. Since the differences between the pre- and post-cleaning measurements are less than the uncertainty for a single measurement, no correction is applied to the time series based on these measurements. The wavelengths for the measurement pairs have been separated by 3 nm for clarity.

6. CONCLUDING REMARKS

The uncertainty of the calibration radiances from the MOBY integrating spheres is estimated to be about 3% (k=1). This is based on the regular calibrations of the spheres by the manufacturer and on routine measurements of the sphere outputs by the MOBY program's SLMs. The MOBY program also has an interagency cooperative agreement with NIST. As part of this collaboration, NIST personnel annually visit the MOBY site to perform comparison measurements. The artifacts in these comparisons include transfer radiometers and integrating spheres. These artifacts are calibrated at NIST before and after each set of comparisons. The results of these comparison campaigns show the NIST measurements to agree with the calibration values for the MOBY integrating spheres at the 3% level or better – and the NIST measurements confirm the estimated uncertainty for the MOBY calibration standards. The focused effort to establish and maintain traceability (see Fig. 7) to SI values of radiometric quantities at a national metrology institute was a major element of achieving this result.

The uncertainty in the calibration changes during each MOBY deployment is less easily determined. Currently, only the pre-deployment calibration measurements have been used to provide the system responses for each MOBY deployment. In general, the differences between the pre- and post-deployment radiance calibrations of the buoys range from +1% to -6% with a definitive bias to a negative difference for the post-deployment values. This trend is to be expected after a deployment of 3 months. Based on our experience, we feel that the instrument changes during each deployment are known at the 6% level. However, this uncertainty does not include the effects of scattered light within the MOS spectrographs. For ocean color measurements at the blue and green wavelengths, these effects can be as large as 3% to 5%. In addition, these effects can be as large as a factor of two in the ultraviolet for the blue spectrograph and in the red and near infrared for the red spectrograph. Recently, NIST began a study of the stray light contribution to the radiometric uncertainty in the MOBY systems. A complete reprocessing of the MOBY data set, including the changes within each MOBY deployment, will commence upon the completion of the stray light characterization, which is scheduled for the fall of 2001. It is anticipated that this reprocessing will reduce the overall uncertainties to less than 5% (k=1). Until these changes are made, the overall uncertainty for the radiometric calibration of MOBY in-water ocean color measurements is about 4% to 8% (k=1).

ACKNOWLEDGEMENTS

The authors would like to extend their appreciation to the MOBY team members: Eric Stengel, Edwin Fisher, Edward King, Marilyn Yuen, Mike Ondrusek, (NOAA/NESDIS) - Stephanie Flora, John Heine, Darryl Peters, Terry Houlihan, William Broenkow, (San Jose State Univ., Moss Landing Marine Laboratories) - Charles Trees, Chris Kinkade, (San Diego State Univ., Center for Hydro-Optics and Remote Sensing) and to the University of Hawaii's RV Mona Wave and RV Kaimikai-O-Kanaloa ship personnel for their professional support in the challenging tasks associate with the MOBY deployments and retrievals. Over the past 12 years this work has been supported by NASA Goddard Space Flight Center under contracts S-19864-E (EOS/MODIS Project) and S-42017-E, NAS5-31746 (SeaWiFS Project). Additional support for the NIST participation in this project has been provided under contracts S-41365-F (EOS Project Science Office) and S-64096-E (SeaWiFS Project).

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