Advances in radiometry for ocean color

Steven W. Brown and B. Carol Johnson

National Institute of Standards and Technology, Gaithersburg, MD, USA 20899-8442

ABSTRACT

Organic materials in the oceans have spectral signatures based on their light-scattering properties. These optical properties are related to bio-physical and bio-chemical data products such as the concentration of phytoplankton chlorophyll-*a* through bio-optical algorithms. A primary quantity of interest in ocean color research is the water-leaving spectral radiance $L_w(\lambda)$, often normalized by the incident solar flux. For quantitative studies of the ocean, derivation of the relationship between the optical properties and physically meaningful data products is critical. There have been a number of recent advances in radiometry at the National Institute of Standards and Technology that directly impact the uncertainties achievable in ocean-color research. These advances include a new U.S. national irradiance scale; a new laser-based facility for irradiance and radiance responsivity calibrations; and a novel tunable, solid-state source for calibration and bio-optical algorithm validation. These advances, their relevance to measurements of ocean color, and their effects on radiometrically derived ocean-color data products such as chlorophyll-*a* are discussed.

Keywords: calibration; irradiance standards; radiometry, remote sensing

1. INTRODUCTION

Determination of global ocean data products such as the distribution of phytoplankton chlorophyll-a provides critical information for bio-chemical and bio-physical models of regional and global processes as well as for climate research. For example, the duration and magnitude of phytoplankton primary productivity impacts the air-sea carbon distribution. Knowing the magnitude and distribution of phytoplankton biomass is crucial to understanding carbon budgets and determination of global chlorophyll-a concentration is a key parameter used in primary productivity models [1, 2].

Under natural illumination from sunlight, the optical properties of seawater and dissolved and suspended materials result in spectrally dependent absorption, scattering, and fluorescence. A primary radiometric quantity of interest in ocean color is the water-leaving spectral radiance $L_w(\lambda)$. Satellite sensors such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) are used for global measurements of ocean color. Remote sensing of ocean color (or $L_w(\lambda)$) is challenging in part because the radiance measured by space-borne sensors is dominated by other sources: approximately 90 % of the at-sensor signal arises from scattering in the intervening atmosphere between the satellite and the ocean. The optical properties are related to bio-physical and bio-chemical data products such as the concentration of phytoplankton chlorophyll-a through bio-optical algorithms.

The uncertainty goals of SeaWiFS are representative of the community: a relative standard uncertainty in $L_w(\lambda)$ of 5 % for open ocean waters where the dominant interaction is absorption (primarily by chlorophyll) [3]. This level of uncertainty in $L_w(\lambda)$ results in an uncertainty in the concentration of chlorophyll-a of 35 % using a bio-optical algorithm developed in ancillary studies [4]. Because the $L_w(\lambda)$ component is typically about 10 % of the at-satellite radiance, the satellite should be calibrated with an uncertainty of about 0.5 % to achieve an uncertainty of 5 % in $L_w(\lambda)$. Instead, calibration uncertainties in the visible for ocean color sensors are approximately 5 % [5]. To obtain the accuracies required to support the science data requirements, ocean color satellites are calibrated vicariously using accurate and continuous measurements of $Lw(\lambda)$ with ocean-based instruments [6]. The primary reference instrument for most ocean color satellites, including SeaWiFS and MODIS, is the Marine Optical Buoy (MOBY), a radiometric buoy stationed in the waters off Lanai, Hawaii [7].

Radiance is not the only quantity of interest in ocean-color research; irradiance and reflectance are also critical. Measurements of down-welling spectral irradiance at the surface and at various depths are used by MOBY and other "in-water" instruments to derive normalized $L_w(\lambda)$ and additional parameters such as the diffuse attenuation coefficient [7]. For instruments that measure the radiometric properties of the ocean above the water, a known standard of diffuse reflectance is typically used to determine $L_w(\lambda)$ or the related quantity, the remote sensing reflectance [8], [9]. Accurate characterization of the atmosphere, which is required for satellite retrievals, requires sun photometry (irradiance) and sky radiance measurements. In the radiometric calibration laboratory, the most common method of generating a source of known spectral radiance is to illuminate a diffuse reflectance standard with a lamp standard of spectral irradiance.

Current bio-optical algorithms for pigment retrievals are based on radiance ratios at a few selected narrow (10 nm) spectral intervals from about 440 nm to about 555 nm: the ratio of water leaving radiance at 443 nm and 555 nm (L_w(443 nm)/ L_w(555 nm)), for example [4], is used to radiometrically determine chlorophyll concentrations in oligotrophic waters. Other spectral bands are related to specific products, such as observing natural fluorescence from chlorophyll (around 685 nm) or evaluating the presence of gelbstoff, or Color Dissolved Organic Material, (around 380 nm). Characterization of the atmosphere requires measurements at fixed spectral intervals from at least 380 nm in the ultraviolet [10] to 870 nm or even 1064 nm in the near infrared [11]. Finally, spectroradiometric systems such as MOBY, which are used for vicarious calibration of multiple satellites, are recommended to have as a minimum requirement spectral coverage from 380 nm to 900 nm [10].

In this paper, we discuss recent work at the National Institute of Standards and Technology (NIST) that has direct impact on the radiometric uncertainties achievable in ocean-color research. We consider these advances and their relevance to and effects on measurements of ocean color. We also show that instrument characterization can be as important as radiometric calibration if the desired uncertainty goals are to be met. In Section 2, we discuss the new 2000 NIST irradiance scale. A new laser-based approach for irradiance and radiance responsivity calibrations is discussed in Section 3. Examples of improved calibrations of instrumentation involved in ocean color measurements using the laser-based calibration facility are presented. Finally, a unique solid-state source for calibration and bio-optical algorithm validation is discussed in Section 4.

2. 2000 NIST IRRADIANCE SCALE

Uncertainties in the spectral irradiance of a standard artifact affect the uncertainty of ocean color irradiance measurements directly, and they also impact the uncertainty of radiance measurements because the majority of users utilize irradiance and reflectance standards to realize radiance (commonly termed the "lamp/plaque" method).[1] Of course, only a portion of the combined uncertainty in the irradiance or radiance responsivity of a sensor arises from the radiometric standard, but it is important to make this component small compared to the overall uncertainty goal. This makes the target uncertainties practically achievable, facilitates identification of sources of bias, and is helpful for some types of comparisons.

Lamp standards (1000 W FEL-type (ANSI designation)) are used to disseminate the spectral irradiance scale from NIST to the user community. In 2000, NIST implemented a new method of realizing spectral irradiance that resulted in a reduction of uncertainties by a factor of 2 for the spectral interval from 250 nm to 900 nm, and by up to a factor of 10 for the spectral interval from 900 nm to 2400 nm [12]. The previous spectral irradiance scale determination involved transferring values of spectral radiance from a gold-point blackbody standard using a spectroradiometer, eventually resulting in the assignment of spectral irradiance values to a lamp-illuminated integrating sphere source [13]. The new method utilizes a high-temperature, large-area blackbody as the irradiance standard. The temperature of the blackbody is determined directly using filter radiometers with known spectral irradiance responsivity. To determine the spectral irradiance responsivity, the filter radiometers were calibrated by separate measurements of the spectral power responsivity and the area of its limiting aperture.

The reduction in uncertainty is illustrated in Fig. 1 (from [12]). For issued lamps, the uncertainties are greater to allow for temporal drift in the issued standards, and this effect is most serious at the shortest wavelengths. Several factors contribute to the reduction in the uncertainty in the 2000 irradiance scale, including the fact that there are fewer measurement steps in the new method. Also, the high temperature blackbody is very stable compared to the lamp-illuminated integrating sphere source. The temperature of the high temperature blackbody (3000 K) is determined using

---

[1] An alternative to the lamp/plaque method is to use a lamp-illuminated integrating sphere source, with the spectral radiance values assigned by direct comparison to a blackbody of known temperature.

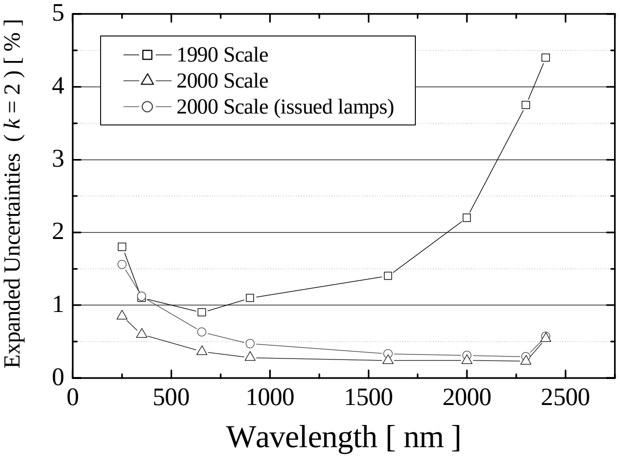

Figure 1. Comparison of expanded uncertainties of the 1990 NIST irradiance scale realization along with the expanded uncertainties of the 2000 scale realization. The expanded uncertainties of the issued lamps are greater because of the additional component of the long-term temporal stability of the working standards (from [12]).

detector standards whose responsivities are based on absolute measurements of geometric quantities (area and distance) and radiant flux (measured using electrical substitution radiometry at cryogenic temperatures). Each of these components has an extremely low uncertainty. For example, the geometric area of circular apertures of high optical quality (e.g, diamond turned) and moderate size (3 mm to 25 mm diameter) can be determined at NIST with a relative expanded uncertainty ($k = 2$) of about 0.005 % [14]. The spectral flux responsivity for the filter radiometers used in the 2000 irradiance scale realization was determined on the Visible Spectral Comparator Facility (Vis/SCF) [15] and was the primary uncertainty component in the determination of the temperature of the high temperature blackbody. In the future, the laser-based calibration facility described in Section 3 will be used to directly determine the spectral irradiance responsivity of the filter radiometers, and further reduction in the uncertainty in the NIST spectral irradiance scale is anticipated.

In their paper, Yoon et al. [12] compare spectral irradiance values assigned using the new detector-based method to the values assigned using the previous method of transferring the irradiance scale from a gold-point blackbody. The gold-point blackbody method was used in 1990 and 1992 to assign spectral irradiances to a set of check standards (lamps that were used infrequently) as well as the primary working standards (used to calibrate issued lamps). Comparisons with the 2000 irradiance scale indicate that the 1992 irradiance scale resulted in values that were about 1 % too low in the visible and near infrared spectral regions (400 nm to 900 nm). The discrepancies are within (but about equal to) the expanded ($k = 2$) uncertainty of the previous scale.

A discrepancy of 1 % in spectral irradiance, which is the result of continued utilization of lamps calibrated based on the 1990/1992, translates directly to a bias in spectral irradiance responsivity. Although there are many other components of uncertainty that may affect the final result (including, but not limited to, the accuracy of the lamp current, degree of adherence to the NIST protocols, the variation of the irradiance with distance, the determination of immersion coefficients and cosine response, etc.), bias of this magnitude is significant compared to the overall uncertainty goals, which are 1 % for laboratory calibrations [16].

The effect on spectral radiance responsivity depends on the method used by the laboratory to realize spectral radiance. Use of the lamp/plaque method propagates the error that exists in the 1990 scale into the radiance responsivities, and lamps on the 2000 scale should be used. However, if the standards of spectral radiance are calibrated directly against blackbody standards (such as done at NIST using FASCAL), a bias will exist between the user’s irradiance and radiance responsivity assignments until the irradiance standards are recalibrated using the 2000 NIST scale. This effect has been observed using radiometers calibrated for spectral radiance responsivity in comparisons of the spectral radiance of lamp-illuminated plaques [17].

In summary, standard irradiance lamps issued by NIST based on the 2000 irradiance scale will have uncertainties a factor of two or more lower than lamps based on the1990/1992 irradiance scale. In addition, new lamps will not have a known 1 % bias that exists in the 1990/1992 irradiance scale.

3. NIST FACILITY FOR SPECTRAL IRRADIANCE AND RADIANCE RESPONSIVITY CALIBRATIONS USING UNIFORM SOURCES (SIRCUS)

Detectors have historically been calibrated for spectral power responsivity at NIST using a lamp-monochromator system to tune the wavelength of the excitation source [15]. Instruments can be calibrated in the visible spectral region with uncertainties at the 0.1 % level. However, uncertainties increase dramatically when measuring an instrument's spectral irradiance or radiance responsivity. Because of the low flux in the lamp-monochromator system (and non-uniformity in the spatial profile of the output beam), instruments cannot be directly calibrated for irradiance or radiance responsivity and more complicated approaches must be taken that increase the uncertainty in the measurements to the 1 % level. In addition, the low flux associated with lamp-monochromator excitation sources (~ 1 μW) limits the effective dynamic range of the system. The out-of-band response of filter radiometers can only be measured to approximately 0.001 % of the peak response.

A laser-based facility for Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources (SIRCUS) was developed to calibrate instruments directly in irradiance or radiance mode with uncertainties approaching those available for spectral power responsivity calibrations [18, 19]. A schematic of the SIRCUS facility is shown in Fig. 2. High-power, tunable lasers are introduced into an integrating sphere using optical fibers, producing uniform, quasi-Lambertian, high radiant flux sources. Reference standard irradiance detectors, calibrated directly against national primary standards for spectral power responsivity, are used to determine the irradiance at a reference plane [20]. Knowing the measurement geometry, the source radiance can be readily determined as well [19].

The radiometric properties of the SIRCUS source, in particular the narrow spectral width, the negligible wavelength uncertainty, and the high flux levels achievable, coupled with state-of-the-art transfer standard radiometers whose responsivities are directly traceable to primary national radiometric scales, result in combined standard uncertainties in irradiance and radiance responsivity calibrations at the 0.1 % and 0.15 % levels, respectively. In addition, lamp/monochromator systems typically have non-uniform spatial distributions, contributing to the total irradiance uncertainty. General characteristics of the NIST laser-based and lamp-based facilities are listed in Table 1.

Some of the advantages of the laser-based calibration approach are illustrated by the calibration of a Photo-Electric Pyrometer (PEP) used to radiometrically determine the temperature of a blackbody. The instrument is equipped with a narrow bandpass filter (~ 1 nm) for spectral selectivity, making it difficult to study with lamp-illuminated monochromators because of their finite spectral bandpass. For accurate radiance temperature determinations, the instrument's spectral out-of-band responsivity needs to be measured as well. Fig. 3 shows the relative spectral responsivity of the PEP determined on SIRCUS compared with the relative spectral responsivity determined using a conventional lamp-monochromator system. As shown in Fig. 3(a), the spectral responsivity measured with the lamp-monochromator system is dominated by the spectral bandwidth of the source, and deconvolution of the spectrum using the source slit scatter function is required. In contrast, the fine detail in the spectral responsivity is easily measured on SIRCUS because of the monochromatic nature of the source. Note that there are several overlying data points at each wavelength along both the rising and falling edges, demonstrating the extreme wavelength stability of the SIRCUS facility. Because of the low flux, the out-of-band responsivity is limited to approximately 10^{-6} with the lamp-monochromator system (Fig. 3(b)). In contrast, the out-of-band responsivity can be measured to the 10^{-9} level in the SIRCUS facility.

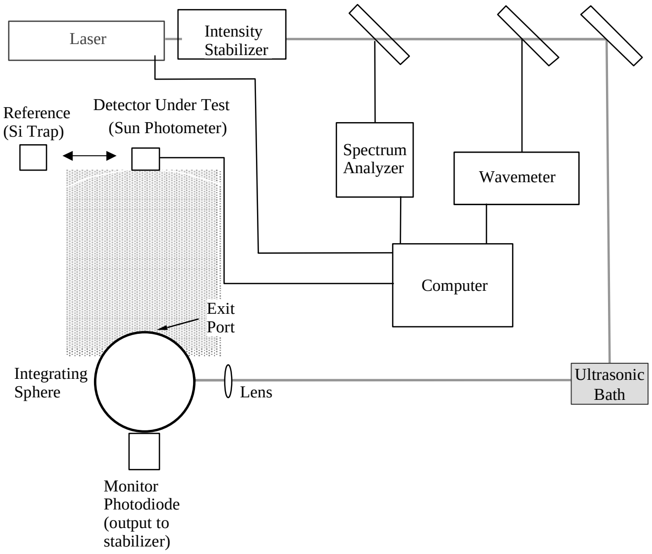

Figure 2. Schematic diagram of the SIRCUS calibration facility.

In SIRCUS, instruments are calibrated in their operational state – at the system level, with entrance pupils over-filled. This approach avoids unforeseen errors that can occur using other calibration approaches. For example, consider measurements of the relative spectral responsivity of a single channel filter radiometer known as a Standard Lamp Monitor (SLM) [21]. The SLMs can be operated in irradiance or radiance mode, depending on the

Table 1. Comparison SIRCUS and SCF properties.

Parameter	SIRCUS Facility	Lamp/Monochromator
Optical Power	300 mW	1 µW
Bandwidth	< 0.001 nm	1 nm to 5 nm
Wavelength uncertainty	< 0.01 nm	0.1 nm
Power responsivity calibration	yes	yes
Uncertainty	0.1 %	0.1 %
Irradiance responsivity calibration	yes	yes
Uncertainty	0.1 %	0.5 %
Radiance responsivity calibration	yes	no
Uncertainty	0.2 %	
Digital imaging systems	yes	no

fore-optics. They are used in the MOBY Project to monitor the stability of radiometric standards of spectral irradiance (FEL lamps) and radiance (lamp-illuminated integrating sphere sources). The irradiance mode configuration has a Teflon™[2] diffuser, a window, an interference filter, and a silicon photodiode. Two models exist: one with a filter that has a peak transmittance at 412 nm and a second with a peak filter transmittance at 870 nm.

The instruments' relative spectral responsivities (RSRs) are used to band-integrate the response to an illumination source. The RSRs of the SLMs were determined using a lamp-monochromator system. During these measurements, the flux from the monochromator exit slit was imaged onto the center of the diffuser. In this case, the irradiance collector was under-filled by the incident radiant flux. The SLMs were also calibrated in irradiance mode for absolute spectral responsivity on SIRCUS. In this case, the irradiance collector was overfilled by the flux from the laser-illuminated integrating sphere. Comparing the two results using peak-normalized data, it was noted that the relative spectral responses did not agree (Fig. 4). There was no dependence on the f/# of the incoming flux. However, spatial maps of the relative response on the lamp/monochromator system at multiple fixed wavelengths within the in-band region showed that the irradiance responsivity is not spatially uniform (due to the diffuser), leading to the observed

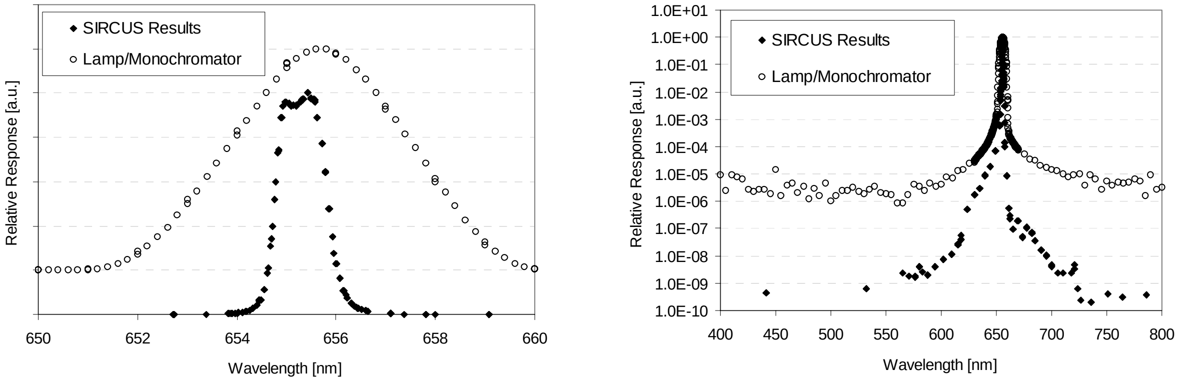

Figure 3. Comparison of the normalized relative spectral responsivity of the PEP measured on the SCF (top graph) and the SIRCUS (bottom graph); (left) linear and (right) log scale.

---

[2] 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 are necessarily the best available for the purpose.

differences. These measured differences can cause errors in the band-averaged measurements of spectral irradiance when the spectrum of the source being measured differs from that of the calibration source.

To achieve the lowest possible uncertainties on SIRCUS, the instrument should be designed with the calibration in mind. Interference fringes from multiple reflections of incident radiation at optical surfaces have been observed in the calibration of instruments with windows and other optical elements if they are not wedged or anti-reflection coated. The presence of interference fringes can increase the uncertainty in the calibration, or the difficulty in the calibration if they need to be mapped out. For example, Fig. 5 shows an irradiance meter calibrated on SIRCUS that shows the presence of interference fringes.

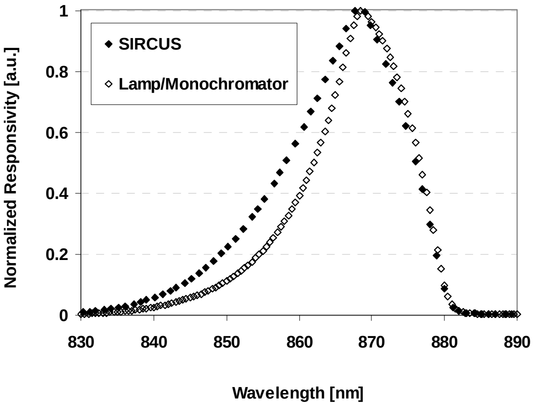

Figure 4. SIRCUS and SCF (Lamp/Monochromator) measurements of the spectral responsivity of the 870 nm SLM in irradiance mode. The data have been normalized to the maximum value.

In many applications, for example the characterization of MOBY discussed below, it is not possible to bring the instrument to NIST to be characterized and calibrated. To enable characterization and calibration of those instruments using the laser-based approach, a portable, table-top, laser-based calibration system, called Traveling SIRCUS, was developed. A fiber-coupled, laser-based integrating sphere source (ISS), similar to the radiance source in the SIRCUS facility, is used for Traveling SIRCUS. Tunable laser sources enable continuous spectral coverage over the spectral ranges from 380 nm to 460 nm and from 560 nm to 1100 nm. The spectral region from 460 nm to 560 nm is covered using a number of fixed-frequency lasers.

Sections 3.1 and 3.2 give example applications of the SIRCUS facility relevant to ocean-color remote sensing.

3.1. MOBY stray light characterization using Traveling SIRCUS

MOBY uses an instrument known as the Marine Optical System (MOS) to detect radiation over the spectral range from 350 nm to 955 nm. The MOS system contains two single-grating spectrographs, a blue spectrograph (BSG) to measure light in the near ultraviolet and visible from 340 nm to 640 nm and a red spectrograph (RSG) to measure light in the red

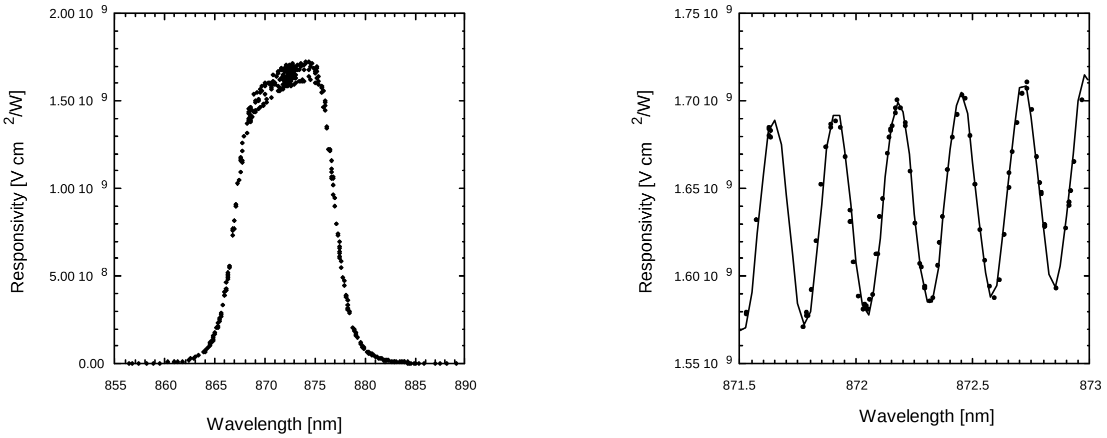

Figure 5. SIRCUS calibration of an irradiance meter showing interference fringes. (left) absolute spectral responsivity of the irradiance meter; (right) expanded view of the interference fringes. The solid line is a fit to the data.

and near infrared from 550 nm to 955 nm [7, 21]. There are a total of three active MOS systems: MOS202, MOS204, and MOS205. MOS202 is a ship-deployable instrument used in the development of bio-optical algorithms. MOS204 and MOS205 are used with MOBY. Buoy deployments are numbered sequentially; MOS204 is used with even buoy deployments while MOS205 is used in odd buoy deployments. These systems reside in the MOBY instrument bay located at the bottom of the buoy. MOS is connected using optical fibers to radiance and irradiance ports on the three MOBY arms (denoted Top, Mid, and Bot), located at differing depths in the ocean (typically 1.5 m, 5 m and 9 m), as well as a surface irradiance port. MOBY measures upwelling radiance L_u as well as the down-welling irradiance E_d at different depths in the ocean. As described in Clark *et al*. [7], these data are used to determine the solar-normalized water-leaving radiance, nL_w.

Typically, instruments used to make radiometric measurements of the ocean (including MOBY) are calibrated against incandescent sources with spectral distributions approximating blackbody sources with temperatures in the range from 2800 K to 3200 K. Instruments calibrated against these sources — that have a maximum radiance in the short-wave infrared — subsequently measure the radiance of the ocean, which peaks between 450 nm and 550 nm, depending on chlorophyll concentration. Because the spectral distribution of in-water or water-leaving radiance differs significantly from the spectral distribution of the calibration source, small amounts of stray radiation arising for example from out-of-band filter leakage or unwanted scattering in a spectrograph can give rise to unforeseen errors, often much larger than anticipated.

For a spectrograph illuminated with monochromatic radiation, the entrance slit is spatially imaged on the detector. Ideally, no radiation falls on detector elements outside the image. In practice, the image is modified by scattered light within the spectrograph and every element in the array can have a finite response to this monochromatic radiation. The response of the two spectrographs in the MOS205 system to monochromatic laser excitation is shown in Fig. 6. The spectra are similar for both spectrographs. There are four components to the image: a strong sharp peak corresponding to the image of the spectrograph entrance slit on the CCD; a broad, peaked structure around the slit image; a non-zero constant component and an additional peak. The first three components are similar to specular, haze, and diffuse components of reflectance, respectively. They remain invariant as the excitation wavelength is changed and the image moves across the CCD. The specular component corresponds to the properly imaged radiation; the haze and diffuse components arise from light scattered in the spectrograph, principally from the grating. These two components are analogous to the spectral out-of-band features commonly observed in a filter radiometer. From physical examination of the spectrographs, the fourth component (the additional peak) is associated with a higher order diffraction from the grating. The reflection peak changes size, shape and position with respect to the primary peak as the image moves across the array.

The MOS instruments were characterized for their stray light response and the results incorporated into an algorithm that was developed to correct for stray light [22]. The entire MOBY system was characterized *in situ* in the calibration facility at the University of Hawaii Marine Center, Honolulu, Hawaii. A tunable, monochromatic source, *e.g.* SIRCUS, was necessary to determine the system's spectral response over some finite range, and the Traveling SIRCUS was deployed to Hawaii for this purpose.

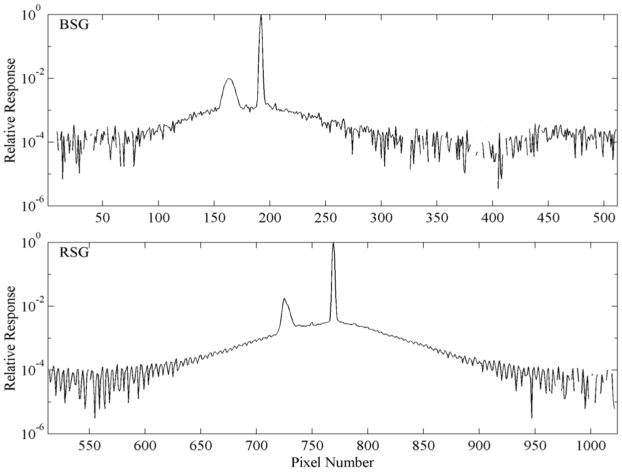

Figure 6. MOS response to monochromatic excitation at (top) 550 nm (for the blue spectrograph) and (bottom) 700 nm (for the red spectrograph).

Slit scatter parameters were determined for the radiance ports on the MOBY arms. The imaging remained the same for different MOBY arms and for the same MOS system from deployment to deployment. Independent stray light parameters were developed for each MOS system. The measurements were incorporated into the correction algorithm. The MOS radiance responsivities were first corrected, then in-water up-welling spectral radiance measurements were corrected. The responsivity changed by

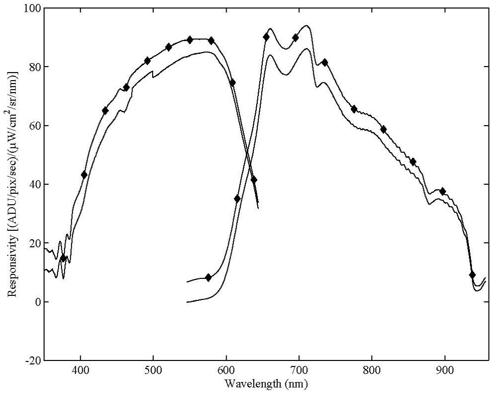

Figure 7. Uncorrected (solid diamonds) and stray light corrected (solid line) MOS responsivity.

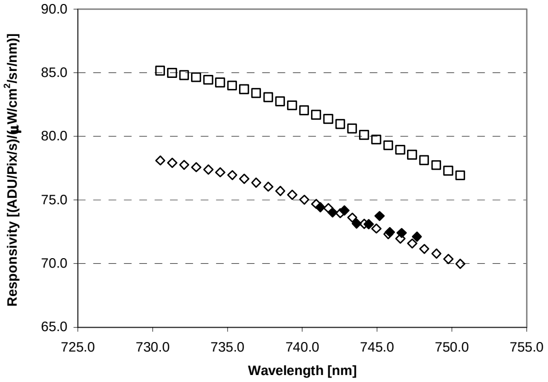

Figure 8. Comparison of SIRCUS-derived in-band responsivity (open diamonds) with lamp-illuminated integrating sphere calibration uncorrected (open squares) and corrected (closed diamonds) for stray light.

approximately 10 % over the central region of the array, increasing dramatically at the edges, as shown in Fig. 7. The stray light corrected responsivity determined using lamp-illuminated integrating spheres can be compared directly with the band-integrated responsivity determined using SIRCUS. The comparison, shown in Fig. 8**,** gave us confidence in the stray light correction algorithm, which was further validated by measurements of a filtered lamp-illuminated integrating sphere source [22].

MOBY is used for the vicarious calibration of a number of ocean color satellites. Consider the impact on SeaWiFS as a representative example of the impact of the stray light correction of MOBY. SeaWiFS bands 1 through 6 are vicariously calibrated against MOBY [23]. Any changes in MOBY-derived water-leaving radiances are directly reflected in SeaWiFS calibration coefficients for these channels. The SeaWiFS band-averaged nL_w stray-light-correction factors measured by MOBY (the correction factors are simply the ratio of the stray-light-corrected to the uncorrected measurements) over 4 years of deployments is given in Fig. 9 (from [22]). Each grouping in the figure is a separate deployment. The correction factors have been stable over the entire deployment sequence, implying that the MOBY imaging and the MOS slit-scatter functions, along with the ocean-color, have remained stable over this time frame. The observed radiometric stability of the MOBY systems enables us to correct previous deployments for stray light with confidence.

The effect of the MOBY stray-light correction is to increase the water-leaving radiance of SeaWiFS Bands 1 through 4, and decrease the radiance of Bands 5 and 6. SeaWiFS uses the Band 2 (443 nm) to Band 5 (555 nm) ratio to radiometrically determine chlorophyll-*a* concentrations in oligotrophic waters (chlorophyll concentrations about 0.3 μg/l); the Band 3 (490 nm) to Band 5 ratio for mesotrophic waters (chlorophyll concentrations ranging from 0.3 μg/l to 1.5 μg/l); and the Band 4 (510 nm) to Band 5 ratio for eutrophic waters (chlorophyll concentrations > 1.5 μg/l) [24]. Correcting for stray light increases the band ratio in oligotrophic waters by 5 % to 6 % and approximately 3.5 % for waters with higher chlorophyll-*a* concentrations.

The change in band ratios corresponds to a 25 % to 35 % decrease in chlorophyll in oligotrophic waters and a 15 % decrease in mesotrophic and eutrophic waters. The stray-light correction of MOBY reduces global mean chlorophyll-*a* concentrations measured by SeaWiFS by 15 % to 20 %. When combined with additional procedural changes implemented in the 4th reprocessing of the SeaWiFS data set in July 2002 [25], the result was a mean monthly decrease in global chlorophyll-*a* concentration of 6 %.

For a variety of reasons, SeaWiFS occasionally measures negative water-leaving radiance at 412 nm. The stray-light correction reduced the occurrence of SeaWiFS-measured negative water-leaving radiance in coastal regions by approximately 50 %.

3.2 Sun photometer calibration comparisons between SIRCUS and NASA's Goddard Space Flight Center

For ocean-color remote sensing, the at-sensor signal is dominated by atmospheric scattering of incident solar radiation. To derive accurate geo-physical and geo-chemical ocean data products from satellite data, the water-leaving radiance must be separated from the signal originating from atmospheric scattering. The atmospheric contribution to the total at-sensor signal must be well known. Consequently, characterization of atmospheric optical properties is critical to the derivation of consistent global ocean color data sets. The Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Project Office uses in-situ atmospheric data to validate SeaWiFS and other ocean color satellite aerosol optical products, to evaluate aerosol models used for atmospheric correction, and to develop vicarious sensor calibration methodologies [26]. Atmospheric data from the SIMBIOS program augment global aerosol measurements by the Aerosol Robotic Network (AERONET) [27].

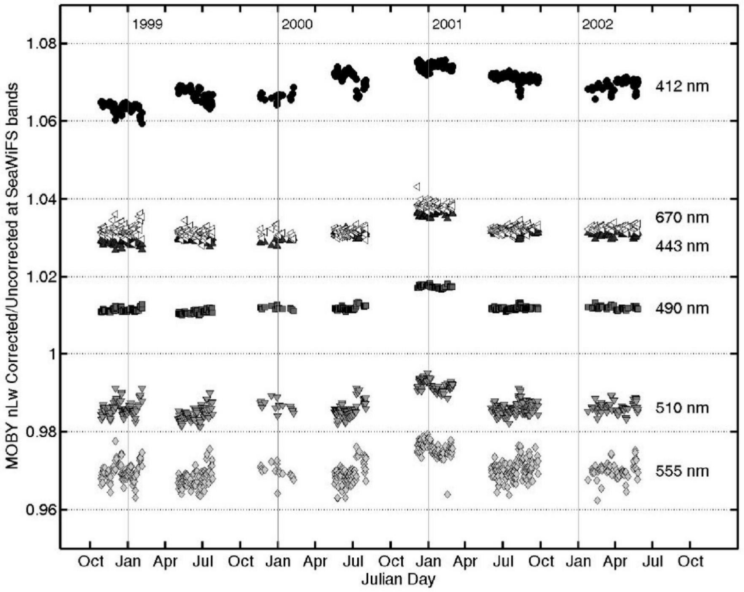

Figure 9. MOBY nL_w stray light correction factors for SeaWiFS bands.

Sun photometers and sky radiometers are used for atmospheric characterization. Sun photometers are used to determine the atmospheric optical depth while radiance determined from sky radiometers constrains the aerosol models input into radiative transfer codes that calculate the atmospheric contribution to the at-sensor signal. Instruments are calibrated for irradiance responsivity against reference sun photometers using the cross-calibration technique at NASA's Goddard Space Flight Center (GSFC) [28]. The cross-calibration technique consists of near simultaneous solar observations at GSFC with the uncalibrated instrument and a calibrated reference sun photometer. Reference sun photometers, which are part of the AERONET project, are calibrated using the Langley-Bouger technique at the Mauna Loa Observatory on regular intervals. The method assumes that the ratio of the output voltages for the same channel (e.g., same spectral responsivity) for the reference and uncalibrated radiometers and a particular air mass is proportional to the ratio of the output voltage at zero air mass. If the spectral responsivities differ, a correction is made for spectral differences related to Rayleigh, ozone, and aerosol attenuation. The uncertainty in the calibration is approximately 2 %.

Instruments are calibrated for radiance responsivity using a NIST-traceable lamp-illuminated integrating sphere source at NASA's GSFC. The primary standard is an FEL standard irradiance lamp. A reference spectroradiometer, the OL746/ISIC, is calibrated for irradiance responsivity against the standard irradiance lamp. The irradiance calibration is then transferred to NASA's Hardy sphere using the 746/ISIC. Knowing the irradiance responsivity of the 746/ISIC, the distance between the sphere exit port and the entrance aperture to the 746/ISIC, and the sphere exit port area, it is straightforward to calculate the spectral radiance of Hardy. The uncertainty in the radiance responsivity calibration is estimated to be approximately 5 %.

Two multi-channel filter radiometers used in the SIMBIOS program were calibrated for irradiance and radiance responsivity on SIRCUS and the results compared with standard calibrations. The Satellite Validation for Marine Biology and Aerosol Determination (SimbadA) radiometers are eleven-channel filter radiometers channel bandpasses of approximately 10 nm and channel center wavelengths at 350 nm, 380 nm, 410 nm, 443 nm, 490 nm, 510 nm, 565 nm, 620 nm, 670 nm, 750 nm and 870 nm, respectively.

In order to compare to the cross-calibration results, the SIRCUS-derived irradiance responsivities $s(\lambda)$ were used to predict a top-of-the-atmosphere (TOA) signal $V_o(SIRCUS)$:

$$V_o\left(SIRCUS\right) = \int s(\lambda)E(\lambda)d\lambda \tag{1}$$

where *s(λ)* is the spectral responsivity of one of the radiometer channels and *E(λ)* is an exo-atmospheric solar irradiance spectrum (mean earth-sun distance). In this work, we used the exo-atmospheric solar irradiance spectrum developed by Thuillier [29]. To perform the integration, the *s*(λ) and the *E(λ)* were interpolated to a uniform wavelength interval of 0.25 nm and integrated. The 750 nm channel results agree with the cross-calibration to within 0.15 %, the 490 nm channel to within 0.85 %, and the 440 nm channel to within 5.76 %.

The dominant source of uncertainty in the SIRCUS-based predicted TOA signal was the solar irradiance spectrum used. Assuming a ~1.5 % combined standard uncertainty in the absolute value and given a step size of 1 nm in the region of interest, we are able to validate the cross-calibration with a combined expanded uncertainty ($k = 2$) of ~ 3.5 %. The agreement for the 490 nm and 750 nm channels is within the combined uncertainties, but the 440 nm results are not and warrant further investigation.

In order to compare the two sets of radiance measurements, the radiance responsivities, *s*(λ), were interpolated to a uniform wavelength interval, as were the sphere spectral radiance values, *L*(λ), for the lamp-illuminated integrating sphere source. The measured signal was then compared to the predicted signal (using Eq. 1, but replacing *E(λ)* with *L(λ)* and using the instrument's radiance responsivity instead of it's irradiance responsivity). We obtained differences in the calibrations between 2 % and 4 %, depending on wavelength. The radiance responsivity results were consistent with results of an intercomparison performed at NASA's Goddard Space Flight Center in 2001 [17, 30].

As a cross-check, the SimbadA instruments were also calibrated against a NIST-maintained lamp-illuminated integrating sphere source that had been recently calibrated on the NIST Facility for Spectroradiometric Calibrations [13]. The preliminary results agree with the SIRCUS measurements within 0.5 %, in agreement with previous comparisons of lamp-based and laser-based radiance responsivity calibrations of filter radiometers [31]. The uncertainty in the radiance responsivity determined on SIRCUS was approximately 0.25 %, a significant reduction from the 5 % uncertainty using the Hardy sphere.

Reductions in the uncertainties in irradiance responsivity calibrations of sun photometers using laboratory standards allow for meaningful comparisons with the results from the solar-based calibration (Langley-Bouguer method), resulting in independent values for the exo-atmospheric solar irradiance at the set of measurement wavelengths. Reducing the uncertainties in radiance responsivity constrains the choice of aerosol models used in the radiative transport code thereby improving the characterization of the atmosphere.

4. DEVELOPMENT OF A SPECTRALLY TUNABLE SOLID-STATE LIGHT SOURCE FOR THE CHARACTERIZATION AND CALIBRATION OF OCEAN-COLOR RADIOMETERS

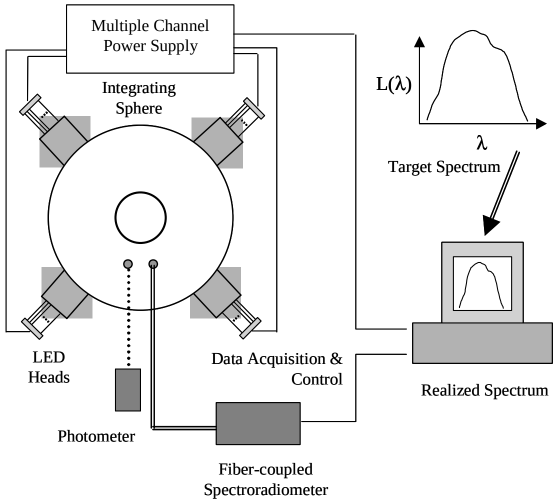

Figure 10. Schematic diagram of the solid-state source.

We have developed a spectrally tunable, solid-state source (SSS) that can approximate a desired spectral distribution over the range from 380 nm to 600 nm. A schematic of the source is shown in Fig. 10. In place of lamps, the source is comprised 40 individually controllable channels made up of from 3 to 10 Light Emitting Diodes (LEDs) with a particular spectral distribution. They are organized into 4 heads with 36 LEDs in each head. The LEDs have bandwidths of approximately 20 nm, and individual channels are separated by approximately 5 nm. The spectral distribution of the source is controlled by changing the current to each set of LEDs. The spectral radiance is determined continuously by a calibrated spectroradiometer that is fiber-coupled to the source. Any desired target spectrum can be input, and the source can be automatically tuned to match the input spectrum (to within 5 %). The source can be rapidly tuned to match the spectral distribution of water-leaving radiance from widely varying chlorophyll waters. Example target and solid-state source spectral distributions for oligotrophic, mesotrophic and eutrophic waters are shown in Fig. 11. The source is currently being evaluated for two applications related to ocean color: as a stable UV calibration source and as a tunable source to derive correction factors for ocean color instruments.

Typically, incandescent lamps are used as calibration sources for ocean color. These sources have low radiant flux and higher calibration uncertainties than desired in the UV (for MOBY, this is the 350 nm to 400 nm spectral range). MOBY for example has uncertainties (neglecting stray light) in its responsivity in this spectral region as large as 5 %. Remote sensing measurements in this spectral region are gaining importance. For example, the Global Imager (GLI) satellite sensor has a 380 nm channel. Reduction in the uncertainty in the MOBY responsivity in the UV will directly reduce the uncertainty in the satellite sensor channel. We are developing a simplified version of the tunable solid-state source with a fixed spectral distribution and stable UV output with the goal of reducing the uncertainty in the radiometric calibration of MOBY in the UV to 2 % or less.

Derivation of remote-sensing-based ocean-color data products such as chlorophyll-*a* involve the amalgamation of measurements by (1) the satellite sensor (*e.g.* SeaWiFS), (2) the vicarious calibration sensors (*e.g.* MOBY), and (3) the instruments used to develop the bio-optical algorithms relating the physical properties of the ocean (*e.g.* chlorophyll-*a* concentration) to a radiometric measurement. Measurement errors in any one of the three components of the measurement chain could significantly affect the quality of the final data product. While considerable time and effort can be (and has been) expended to fully characterize a satellite sensor [32] or primary vicarious calibration station [21], it is much more difficult to extend the detailed characterization to the myriad instruments used by different groups to develop bio-optical algorithms.

Using the tunable solid-state source, we are extending the approach developed by Wang for SeaWiFS to ocean color instruments used for bio-optical algorithm development [32]. Wang used the measured relative spectral responsivities of the SeaWiFS bands along with a semi-analytical model for water-leaving radiance in varying chlorophyll-concentration waters to calculate the out-of-band contribution to the total signal measured by SeaWiFS. From these calculations, extensive lookup tables were developed to remove SeaWiFS' spectral out-of-band response from measurements of L_w. Often, the relative spectral responsivity of instrumentation used to develop bio-optical algorithm instrumentation is unknown. Consequently, Wang's approach must be modified slightly. Instead of *calculating* the out-of-band contribution to the total signal for varying color water, we propose to directly *measure* it using a source that approximates the spectral distributions of water-leaving radiance. To develop the correction factors, the instruments are calibrated in the standard way by their users – typically against incandescent sources. The spectral distribution of the solid-state source is set to approximate the spectral distribution of water-leaving radiance with a particular chlorophyll concentration. Knowing the 'true' band ratio for each setting (because we know the spectral distribution of the source), and measuring the source with the test instrument, a correction factor is determined for the instrument being calibrated for each source distribution. Varying the spectral distribution of the source, a functional relationship between correction factor and band ratio is developed that will then be used to correct *in situ* measurements by ocean color instrumentation. Note the correction factor accounts and corrects for effects of stray light, wavelength error, and varying spectral bandpass of the individual instrument channels. It will not correct for effects such as temperature, however. Instruments only need to measure the ocean color source once, unless there is clear evidence of significant responsivity changes.

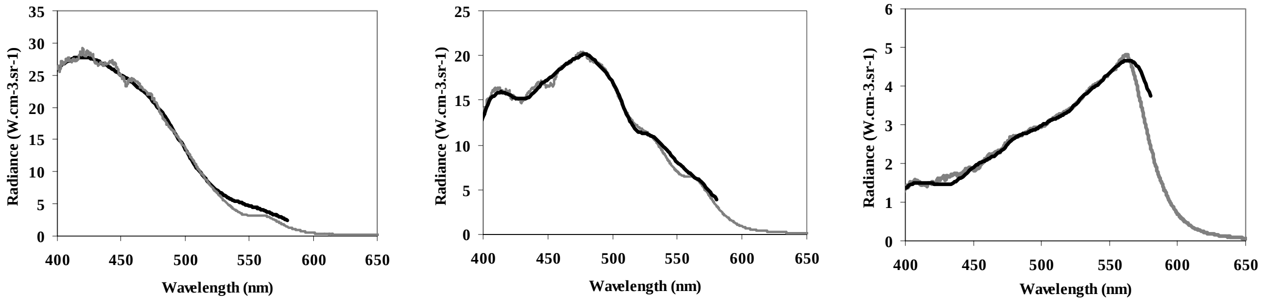

Figure 11. Target (grey) and solid-state source (black) spectral distributions approximating (left) oligotrophic (blue), (middle) mesotrophic (blue-green) and (right) eutrophic (green) waters.

5. SUMMARY

We have presented a number of recent developments in radiometry that directly impact the uncertainties achievable in ocean-color research. Specifically, a new (2000) U. S. national irradiance scale, a new laser-based facility for irradiance and radiance responsivity calibrations, and a novel solid-state source for instrument calibration and bio-optical algorithm validation were discussed. These developments advance the field of ocean color closer to the desired goal of reducing the uncertainty in the fundamental radiometry to a small component of the overall uncertainty in the derivation of remotely sensed ocean-color data products such as chlorophyll-*a*.

6. ACKNOWLEDGEMENTS

We would like to acknowledge and thank the following scientists for their significant contributions to this work: Howard Yoon (irradiance scale realization); Thomas C. Larason (SCF measurements); Nordine Souaidia and Christophe Pietras (sun photometer calibration); Dennis K. Clark, Michael E. Feinholz and Stephanie J. Flora (MOBY); Keith Lykke and George Eppeldauer (SIRCUS and Solid State Source). The work was supported by the U.S. Air Force Metrology and NASA's SeaWiFS, MODIS, SIMBIOS, and EOS Calibration/Validation program offices.

7. REFERENCES

1. *www.carboncyclescience.gov*.
2. Post, W.M., et al., *The global carbon cycle.* Americal Scientist, 1990. **78**: p. 310-326.
3. Hooker, S.B., C.R. McClain, and A. Holmes, *Ocean color imaging: CZCS to SeaWiFS.* Marine Technology Society Journal, 1993. **27**(1): p. 3-15.
4. O'Reilly, J.E., et al., *Ocean color chlorophyll algorithms for SeaWiFS.* Journal of Geophysical Research, 1998. **103**(C11): p. 24937-24953.
5. Guenther, B., et al., *MODIS calibration: a brief review of the strategy for the at-launch calibration approach.* Journal of Atmospheric and Oceanic Technology, 1996. **13**(2): p. 274-285.
6. Gordon, H.R., *In-orbit calibration strategy for ocean color sensors.* Remote Sensing of Environment, 1998. **63**: p. 265-278.
7. Clark, D.K., et al., *MOBY, a radiometric buoy for performance monitoring and vicarious calibration of satellite ocean color sensors: measurement and data analysis protocols*, in *Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 3, Volume 2*, J.L. Mueller and G.S. Fargion, Editors. 2002, NASA Goddard Space Flight Center: Greenbelt, MD. p. 138-170.
8. Mobley, C.D., *Estimation of the remote-sensing reflectance from above-surface measurements.* Applied Optics, 1999. **38**(36): p. 7442-7456.
9. Hooker, S.B., et al., *An evaluation of above- and in-water methods for determining water-leaving radiances.* Journal of Atmospheric and Oceanic Technology, 2002. **19**: p. 486-515.
10. Mueller, J.L. and R. Austin, *Instrument performance specifications*, in *Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 3, Volume 1*, J.L. Mueller and G.S. Fargion, Editors. 2002, NASA Goddard Space Flight Center: Greenbelt, MD. p. 48-59.
11. Morel, A., *Minimum Requirements for an Operational, Ocean-Colour Sensor for the Open Ocean*. 1997, International Ocean-Color Coordinating Group: Darthmouth, Nova Scotia, Canada. p. 46.
12. Yoon, H.W., C.E. Gibson, and P.Y. Barnes, *The realization of the NIST detector-based spectral irradiance scale.* Applied Optics, 2002. **41**: p. 5879-5890.
13. Walker, J.H., et al., *Spectral Irradiance Calibrations*. NBS Special Publication 250-20. 1987, Gaithersburg MD: U.S. Department of Commerce. 37 pages plus appendices.
14. Fowler, J. and M. Litorja, *Geometric area measurements of circular apertures for radiometry at NIST.* Metrologia, 2003. **40**: p. S9-S12.
15. Larason, T.C., S.S. Bruce, and A.C. Parr, *Spectroradiometric detector measurements: Part I--Ultraviolet detectors and Part II--Visible to near-infrared detectors*. NIST Special Publication 250-41. 1998, Gaithersburg MD: U.S. Department of Commerce. 84 pages plus appendices.

16. Mueller, J.L. and R.W. Austin, *Ocean Optics Protocols for SeaWiFS Validation, Revision 1*. SeaWiFS Prelaunch Technical Report Series, NASA/TM 104566, ed. S.B. Hooker, E.R. Firestone, and J.G. Acker. Vol. 25. 1995, Greenbelt, MD: NASA Goddard Space Flight Center. 67 pp.
17. Butler, J.J., B.C. Johnson, and R.A. Barnes, *Radiometric measurement comparisons at NASA's Goddard Space Flight Center: Part II. Irradiance lamp comparisons and the NIST sphere source.* The Earth Observer, 2002. **14**(4): p. 25-29.
18. Brown, S.W., G.P. Eppeldauer, and K.R. Lykke, *NIST facility for Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources.* Metrologia, 2000. **37**: p. 579-582.
19. Eppeldauer, G.P., et al., *Realization of a spectral radiance responsivity scale with a laser-based source and Si radiance meters.* Metrologia, 2000. **37**: p. 531-534.
20. Eppeldauer, G.P. and D.C. Lynch, *Opto-mechanical and electronic design of a tunnel-trap Si- radiometer.* J. Res. NIST, 2000. **105**(6): p. 813-828.
21. Clark, D.K., et al., *An overview of the radiometric calibration of MOBY*, in *Earth Observing Systems VI*, W.L. Barnes, Editor. 2002, Society of Photo-Optical Instrumentation Engineers: Bellingham, WA. p. 64-76.
22. Brown, S.W., et al., *Stray-light correction of the Marine Optical Buoy*, in *Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Rev. 4*, J.L. Mueller and G.S. Fargion, Editors. 2003, NASA's Goddard Space Flight Center: Greenbelt, MD.
23. Barnes, R.A., et al., *The calibration of SeaWiFS on orbit.* Proceedings of the SPIE, 2000. **4135**: p. 281-293.
24. O'Reilly, J.E., et al., *Ocean color chloropohyll algorithms for SeaWiFS.* Journal of Geophysical Research, 1998. **103**: p. 24937-24953.
25. *http://seawifs.gsfc.nasa.gov/SEAWIFS/RECAL/Repro4/*..
26. Fargion, G.S., R.A. Barnes, and C.R. McClain, *In situ aerosol optical thickness collected by the SIMBIOS program (1997-2000): Protocols and data QC and analysis*. NASA/TM-2001-209982. 2001, Greenbelt, MD: NASA's Goddard Space Flight Center. 103 pp.
27. Holben, B.N., et al., *Aeronet - a federated instrument network and data archive for aerosol characterization.* Remote Sens. Environ., 1998. **66**: p. 1-16.
28. Pietras, C., et al., *Calibration of sun photometers and sky radiance sensors*, in *In situ aerosol optical thickness collected by the SIMBIOS program (1997-2000): protocols, and data QC and analysis*, R.B. G. S. Fargion, and C. McClain, Editor. 2001, NASA's Goddard Space Flight Center: Greenbelt, MD.
29. Thuillier, G., et al., *The solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometer from the ATLAS and EURECA missions.* Sol. Phys., 2003. **214**: p. 1-22.
30. Butler, J.J., B.C. Johnson, and R.A. Barnes, *Radiometric measurement comparisons at NASA's Goddard Space Flight Center: Part I. The GSFC sphere sources.* The Earth Observer, 2002. **14**(3): p. 3-8.
31. Johnson, B.C., et al., *Comparison of cryogenic radiometry and thermal radiometry calibrations at NIST using multichannel filter radiometers.* Metrologia, 2003. **40**: p. S216-S218.
32. Wang, M., et al., *Effects of spectral bandpass on SeaWiFS-retrieved near-surface optical properties of the ocean.* Applied Optics, 2001. **40**(3): p. 343-348.