Protocols for Satellite Ocean Color Data Validation: In situ Optical Radiometry

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Preface

This document aims to support the ocean color community with protocols for the collection, processing and quality assurance of in situ measurements of the apparent optical properties of natural water for the validation of satellite radiometric products. In addition to a general introduction on Elements of Marine Optical Radiometry Data and Analysis (Chapter 1), the document addresses Radiometers Specifications (Chapter 2), Calibration and Characterization of Optical Radiometers (Chapter 3), In-water Radiometry Measurements and Data Analysis (Chapter 4), and Above-water Radiometry Measurements and Data Analysis (Chapter 5).

The overall structure and content of the various chapters are based on, and benefit from, the Ocean Optics Protocols promoted by the National Aeronautics and Space Administration within the framework of the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and Sensor Intercomparison for Marine Biological and Interdisciplinary Ocean Studies (SIMBIOS) programs (Mueller and Austin 1995, Mueller et al. 2003a, Mueller et al. 2003b).

It is emphasized that, by recognizing optical radiometry can be heavily affected by the presence of clouds which will unavoidably challenge the quantification of measurement uncertainties, the protocols put emphasis only on measurements performed during clear sky conditions, which are those relevant for the validation of satellite ocean color data products.

Finally, it is anticipated that the chapters on in-water and above-water radiometry provide comprehensive details on those measurement methods sharing large consensus inside the community and whose application is strongly encouraged. Conversely, brief summaries are only provided for those methods already well represented by the previous ones or for those methods that may exhibit difficult implementation in a variety of measurement conditions.

Chapter 1: Elements of Marine Optical Radiometry Data and Analysis

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1. INTRODUCTION

This chapter introduces a few complementary elements relevant to both in- and above-water radiometry. It specifically embraces the spectral classification of radiometers, and a general description of irradiance and radiance sensors. Further, it addresses the need to account for a number of corrections generally resulting from characterizations of the radiometer performance. By then focusing on the basic radiometric quantity, i.e., the water leaving radiance $L_W(\lambda)$, methods are introduced for its normalization to remove the dependence on illumination conditions. Finally, the uncertainty budget for the normalized water-leaving radiance $L_{WN}(\lambda)$ determined from a specific in-water radiometer system is provided as an elementary example for radiometric data products.

2. RADIOMETERS

Spectral classification

Radiance and irradiance sensors are commonly classified according to their capability of spectrally resolving the light (Zibordi and Voss 2014). Specifically, optical radiometers relevant for the validation of satellite ocean color products can be separated into hyperspectral and multi-spectral in order of decreasing spectral resolution.

A large number (generally tens) of narrow spectral bands typically less than 10 nm wide distributed continuously across the spectrum characterize hyperspectral radiometers. These sensors, exhibiting a spectral resolution larger than the sampling interval at which the spectrum is measured, use a dispersive optical element (i.e., diffraction grating or prism) with one- or two-dimensional detector arrays to sample the light spectrum. Hyperspectral radiometers are commonly affected by stray light as a result of scattering or reflections in the optical system causing light from one region of the spectrum to interfere with light from another region. Hyperspectral sensors may also exhibit sensitivity to polarization, which becomes a source of uncertainty when measuring polarized natural light fields. Both stray light effects and polarization sensitivity must then be characterized.

As opposed to hyperspectral radiometers, multi spectral sensors measure the light field at a few discrete spectral bands typically 10 nm wide. Similar to the stray light problems in hyperspectral systems, the spectral responsivity of multispectral sensors must be carefully characterized to identify possible spectral regions of response away from the central band (out-of-band response). In fact, any out-of-band response may introduce errors in radiometric measurements varying with the spectral shape of the incoming light.

Irradiance sensors

Irradiance is a measure of the light flux per unit surface area. Typical quantities measured in the field are the downward or upward irradiance, which are the light energy per unit time going through a flat horizontal surface with a given area either in the downward or upward directions.

For any irradiance collector, the spectral angular response must be measured to determine the error in the cosine response (Mekaoui and Zibordi 2013). The effects of this error in irradiance measurements depend both on the spectral angular response of the collector and the radiance distribution of the light field being measured.

One important characteristic is the immersion factor that quantifies the change in responsivity of a sensor as a function of the refractive index of the external medium (Mueller and Austin 1995). Since radiometers have their absolute calibration performed in air, the immersion factor must be determined to account for the difference in their responsivity while in water.

Radiance sensors

Radiance is the flux per unit area within a specified solid angle centered in a given direction. It is generally measured by limiting the field-of-view of the radiometer and assuming radiance is spatially invariant, or at the least slightly changing, over the projected solid angle. The simplest radiance sensor, commonly referred to as a Gershun tube radiometer (Gershun 1939), is formed by combining an irradiance collector and a tube restricting its full-angle field-of-view (FOV). Its nominal FOV is defined by $\theta_{FOV}=2\cdot tg^{-1}(D / 2h)$ where D is the front aperture of the optics and h the distance between aperture and detector. The related solid angle field-of-view in sr is given by $\Omega = 2\pi\cdot(1-\cos(\theta_{FOV} / 2))$.

In general, an optical window is placed in front of the Gershun tube, so equivalent to the case of irradiance sensors, this affects the measured radiance when the radiometer is operated in water. This implies the need to determine the immersion factor for in water measurements (Mueller and Austin 1995).

3. CHARACTERIZATION AND ABSOLUTE CALIBRATION

This section addresses the basic need to ensure proper application of absolute calibration coefficients and correction factors resulting from instrument characterizations to field measurements. While absolute calibration coefficients are produced through laboratory activities necessarily performed on each sensor, the characterizations may result from both laboratory analysis specific for the sensor, or alternatively from investigations performed for a class of radiometers. Both correction factors from characterizations and absolute calibration coefficients contribute to the determination of the actual responsivity of each sensor, which relates the sensor output to the input radiometric quantity. Thus, calibration accounts for: absolute in-air responsivity to the radiometric source (either radiance or irradiance); in-water responsivity changes due to differences between the refractive index of air and that of water; and, additionally, factors correcting for the non-ideal performance of the radiometer such as stray light, polarization sensitivity, non-linearity, temperature dependence, sensitivity decay with time, and deviation from the ideal angular response.

The calibration concept is implemented through the application of the measurement equation yielding the radiometer output for a given source configuration (Zibordi and Voss 2014). Specifically, the conversion from relative to physical units of the radiometric quantity $\Im(\lambda)$ (either $E(\lambda)$ or $L(\lambda)$) at wavelength λ is performed through

$$\Im(\lambda) = F_{\Im}(\lambda)\, F_{i,\Im}(\lambda)\, \aleph(\lambda)\, \mathrm{DN}(\Im(\lambda)) \quad (1)$$

where $\mathrm{DN}(\Im(\lambda))$ indicates the digital output corrected for the dark signal, $F_{\Im}(\lambda)$ the in–air absolute calibration coefficient (i.e., the absolute responsivity), $F_{i,\Im}(\lambda)$ the immersion factor accounting for the change in responsivity of the sensor when immersed in water with respect to air, and $\aleph(\lambda)$ (for simplicity only expressed as a function of λ) corrections for any deviation from the ideal performance of the radiometer. In the case of an ideal sensor $\aleph(\lambda)=1$, but in general

$$\aleph(\lambda)= \aleph_i(i(\lambda))\, \aleph_j(j(\lambda)) \ldots \aleph_k(k(\lambda)) \quad (2)$$

where $\aleph_i(i(\lambda))$, $\aleph_j(j(\lambda))$, …, and $\aleph_k(k(\lambda))$ are correction terms for different factors indexed by i, j, …, k affecting the non-ideal performance of the instrument, such as temperature, non-linearity, polarization, etc..

4. BASIC RADIOMETRIC QUANTITIES

The basic data product from in-water radiometry is $L_w(\lambda)$, generally in units of W m^{-2} nm^{-1} sr^{-1}, whose amplitude varies with the illumination conditions. In view of removing such a dependence, Gordon and Clark (Gordon and Clark 1981) introduced the concept of normalized water-leaving radiance, $L_{wn}(\lambda)$, to express the water-leaving radiance that would occur with no atmosphere, the sun at the zenith and at the mean sun-earth distance

$$L_{wn}(\lambda) = \frac{L_w(\lambda)}{E_s(\lambda)} E_0(\lambda) \tag{3}$$

where $E_0(\lambda)$ is the mean extra-atmospheric solar irradiance in units of W m^{-2} nm^{-1} (Thuillier *et al.* 2003) and the ratio $L_w(\lambda)/E_d(0^+, \lambda)$ is commonly referred to as the remote sensing reflectance $R_{rs}(\lambda)$ in units of sr^{-1}.

In the case that $E_s(\lambda)$ values are not directly measured or, despite the increase in uncertainty, determined from subsurface values of the downward irradiance $E_d(0^-, \lambda)$, the ratio $E_0(\lambda)/E_d(0^+,\lambda)$ can be replaced by $[D^2 \cdot t_d(\lambda) \cdot \cos\theta_0]^{-1}$ (Tanré *et al.* 1979), where D^2 accounts for the variation in the sun-earth distance as a function of the day of the year and $t_d(\lambda)$ is the atmospheric diffuse transmittance computed from measured or estimated values of the aerosol optical depth $\tau_a(\lambda)$ and calculated values of the Rayleigh optical depth, $\tau_R(\lambda)$.

As previously indicated, both $L_{wn}(\lambda)$ and $R_{rs}(\lambda)$ are quantities which take into account illumination effects such as sun-earth distance, atmospheric transmittance, and to some extent the sun zenith angle. However, this initial correction does not account for the bidirectional effects implicit in anisotropic radiance distributions. Corrections for bidirectional effects were introduced by Morel *et al* (2002) through the concept of *exact normalized water-leaving radiance*, $L_{WN}(\lambda)$. By applying their correction scheme to nadir-view $L_{wn}(\lambda)$, $L_{WN}(\lambda)$ is given by

$$L_{WN}(\lambda) = L_{wn}(\lambda) \frac{f(0,\lambda,\tau_a,IOP)}{Q_n(0,\lambda,\tau_a,IOP)} \left[\frac{f(\theta_0,\lambda,\tau_a,IOP)}{Q_n(\theta_0,\lambda,\tau_a,IOP)} \right]^{-1} \tag{4}$$

where the ratios $f(0,\lambda,\tau_a,IOP)/Q_n(0,\lambda,\tau_a,IOP)$ and $Q_n(\theta_0,\lambda,\tau_a,IOP)/f(\theta_0,\lambda,\tau_a,IOP)$ account for the effects of the anisotropic radiance distribution and $\theta_0 \neq 0$.

It is recalled that the above scheme and the related tabulated values of $f(0,\lambda,\tau_a,IOP)/Q_n(0,\lambda,\tau_a,IOP)$ and $Q_n(\theta_0,\lambda,\tau_a,IOP)/f(\theta_0,\lambda,\tau_a,IOP)$ (see Morel *et al*. 2002) were proposed for Case-1 waters where the inherent optical properties (*IOP*) values are expressed as sole function of the chlorophyll-a concentration (*Chla*). Because of this, in view of addressing corrections for bidirectional effects in optically complex waters, a number of alternative approaches were investigated. However, they often require input parameters not accessible unless radiometric measurements are supported by a comprehensive characterization of the water *IOP*s and concentration of the optically significant constituents. Among those approaches, that proposed by Lee *et al.* (2011) for both Case-1 and optically complex waters, solely requires the input radiometric quantity for which corrections need to be devised (i.e., $L_{wn}(\lambda)$). This approach, which separates contributions due to geometry from those depending on *IOP*s, can also be broadly applied to the basic parameter obtained from above-water radiometry, $L_{wn}(\lambda,\theta,\phi)$, where θ and ϕ are the viewing nadir and azimuth angles, respectively. In this correction approach, the following equation is used to determine essential inherent optical properties characterizing the measured $L_{wn}(\lambda)$

$$L_{wn}(\lambda) = E_0(\lambda)\left\{\left[G_0^w(0,0,\theta_0) + G_1^w(0,0,\theta_0)\cdot\frac{b_{bw}(\lambda)}{k(\lambda)}\right]\cdot\frac{b_{bw}(\lambda)}{k(\lambda)} + \left[G_0^p(0,0,\theta_0) + G_1^P(0,0,\theta_0)\cdot\frac{b_{bp}(\lambda)}{k(\lambda)}\right]\cdot\frac{b_{bp}(\lambda)}{k(\lambda)}\right\} \tag{5}$$

where the coefficients G_0^w, G_1^w, G_0^p, G_1^p are model parameters determined for nadir view and sun zenith angle θ_0 from simulations assuming a single scattering phase function representative of an assemblage of particles. Symbols b_{bw} and b_{bp} indicate the pure sea water and particle backscattering coefficients, respectively, where $k=a+b_b$ with $b_b=b_{bw}+b_{bp}$ and a is the total seawater absorption coefficient.

The correction process starts by estimating the values of a and b_b from Eq. 5. Then the derived IOPs are used to calculate $L_{WN}(\lambda)$ by applying the parameters G_0^w, G_1^w, G_0^p, G_1^p determined for θ_0=0 applying

$$L_{WN}(\lambda) = E_0(\lambda)\left\{\left[G_0^w(0,0,0) + G_1^w(0,0,0)\cdot\frac{b_{bw}(\lambda)}{k(\lambda)}\right]\cdot\frac{b_{bw}(\lambda)}{k(\lambda)} + \left[G_0^P(0,0,0) + G_1^P(0,0,0)\cdot\frac{b_{bp}(\lambda)}{k(\lambda)}\right]\cdot\frac{b_{bp}(\lambda)}{k(\lambda)}\right\} \quad (6)$$

This correction approach was investigated in recent studies (Gleason *et al.* 2012, Talone *et al.* 2018) and, as expected showed a better performance in optically complex waters compared with Morel *et al.* (2002), which was proposed for Case-1 waters.

5. UNCERTAINTIES

Errors and uncertainties are distinct quantities. Differences between values of measured quantities and the true values of measurands are indicated as errors. These may comprise *i.* systematic components indicating biases due to lack of accuracy, and *ii.* random components indicating dispersion due to lack of precision. Bias components are generally minimized through corrections.

Uncertainties quantify the incomplete knowledge of the measurand through the available information (i.e., JCGM 2008). These are generally classified into type A when determined through statistical methods and type B when determined by means other than statistical (e.g., models, published data, calibration certificates, or even experience). Type A and type B uncertainties can additionally be separated into additive (i.e., independent of the measured value such as the values related to the dark signal) or multiplicative (i.e., dependent on the measured value such as those related to the responsivity of the radiometer). All uncertainties contribute to the overall measurement uncertainty through their combined values. When the various uncertainties are independent, multiplicative, and normally distributed, the combined uncertainty can be determined as the quadrature sum (i.e., the root square sum) of the various contributions. The level of confidence of each uncertainty is defined by the coverage factor k. Standard uncertainties refer to a confidence level of 68% determined by $k = 1$, while expanded uncertainties defined by $k>1$ refer to confidence levels of approximately 95% ($k\approx2$) or 99% ($k\approx3$).

Uncertainties, when possible, should be provided in both relative (i.e., %) and physical units. The range of values for which the uncertainties are proposed should also be reported together with details on measurement conditions. In fact, uncertainties determined for a specific range of values may not necessarily be the same for other ranges or different measurement conditions.

The quantification of uncertainties of *in situ* measurements should comprehensively address contributions from the calibration source and its transfer, the performance of the radiometer and of any model applied for data reduction, effects of environmental variability, and field perturbations by the instrument housing and deployment platform.

The uncertainty threshold of 5% was originally defined for satellite derived $L_{WN}(\lambda)$ in the blue spectral region to restrict to within 35% the uncertainties in chlorophyll-*a* concentrations determined in oligotrophic waters with existing bio-optical algorithms (Gordon and Clark 1981). This 5% uncertainty threshold was then set as the target for $L_{WN}(\lambda)$ for most of the ocean color missions, regardless of the wavelength. The maximum uncertainty values given for $L_{WN}(\lambda)$ unavoidably prompted the need for uncertainties better than 5% for *in situ* optical radiometry data.

Table 1, which is filled using accessible information from various literature sources, provides a basic example of uncertainty budget produced for $L_{WN}(\lambda)$ data determined from a multispectral free-fall profiler. Neglecting uncertainty contributions due to instrumental performance such as temperature dependence, non-linearity, stray light, polarization sensitivity all assumed marginal for the considered multispectral radiometer system, and also ignoring avoidable contributions to instrument deployment such as tilt assuming these are minimized by an aggressive filtering of data, the table summarizes spectral contributions at the 443, 555 and 665 nm center-wavelengths as resulting from: *i.* uncertainty of the absolute calibration of the L_u sensor accounting for specific contributions from an FEL lamp irradiance standard, reflectance plaque, and mechanical positioning of the various components (Hooker *et al*. 2002); *ii*. uncertainty due to the computation of the immersion factor estimated from differences between theoretical and experimental determinations (Zibordi 2006); *iii.* uncertainty of the correction factors applied for removing self-shading perturbations computed as 25% of the corrections applied to a 5 cm diameter radiometer with 1 cm aperture; *iv.* uncertainty of the absolute calibration of the E_s sensor accounting for contributions from an FEL lamp irradiance standard, and positioning of the various components (Hooker *et al*. 2002); *v.* uncertainty of the corrections applied for the non-cosine response of the E_s collectors as resulting from maximum difference with respect to theoretical correction values performed with highly accurate radiative transfer simulations (Zibordi and Bulgarelli 2007); *vi.* uncertainty in the application of bi-directional corrections computed as 25% of the applied corrections; vii. uncertainty in the determination of the value of E_0 as resulting from an uncertainty of ±1 nm in the center-wavelength of a rectangular 10 nm spectral response function; *viii*. uncertainty in the extrapolation of sub-surface values due to wave perturbations and uncertainties due to changes in illumination and seawater optical properties during profiling, cumulatively quantified as the average of the variation coefficient of $L_{WN}(\lambda)$ from replicate measurements.

Estimated values, quantified assuming that each uncertainty contribution is independent from the others are in the range of 4-5% in the selected spectral bands. It is emphasized that the uncertainty values provided for absolute calibration are likely overestimated. Additionally the proposed uncertainty analysis assumes fully independent calibrations of E_d and L_u sensors (i.e., as obtained with different lamps and laboratory set-ups). The use of the same calibration lamp and set-up would lead to a reduction of approximately 1% of the quadrature sum of spectral uncertainties for $L_{WN}(\lambda)$, explained by correlations between absolute calibration uncertainties of $E_d(\lambda)$ and $L_u(\lambda)$ (Zibordi and Voss 2014).

Table 1. Uncertainty budget (in percent) for L_{WN} determined from in-water profile data

Uncertainty source	**443**	**555**	**665**
Absolute calibration of L_u	2.7	2.7	2.7
Immersion factor	0.4	0.4	0.4
Self-shading correction	0.5	0.3	1.3
Absolute calibration of E_s	2.3	2.3	2.3
Cosine response correction	0.5	0.5	0.5
Anisotropy correction	0.4	0.9	0.5
E_0 determination	1.9	0.8	0.2
Environmental effects	2.1	2.2	3.2
Quadrature sum	4.7	4.4	5.0

6. FUTURE DIRECTIONS

Future research and development activities should specifically address corrections for bi-directional effects and their uncertainties. With this respect, uncertainties in general are a key element that should be further developed to produce a number of key examples hopefully covering the main measurement protocols and instruments.

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Chapter 2: Radiometer Specifications

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1 INTRODUCTION

This chapter introduces requirements for the radiometric quantities relevant to the validation of data from satellite ocean color sensors. The specifications relate to radiometers operated on a variety autonomous or manned systems to acquire the *in situ* data needed for the purpose. These specifications should apply to instruments that exist or that can be developed with current state-of-the-art technology. The overall objective is to ensure the collection of radiometric data with uncertainties complying with requirements for the assessment of satellite ocean color radiometry data.

The following sections will address specifications for both in-water and above-water instruments. Still, emphasis will be on in-water radiometry, complemented by details relevant to above-water radiometry. In particular, the emphasis is placed on the characteristics of instruments measuring in-water $E_d(z,\lambda)$, $E_u(z,\lambda)$ and $L_u(z,\lambda)$. Most of the specifications provided for $E_d(z,\lambda)$, nevertheless, also apply to above-water $E_s(\lambda)$. Similarly, many of the specifications provided for $L_u(z,\lambda)$ apply to measurements of $L_i(\lambda)$ and $L_T(\lambda)$ needed for above-water radiometry. Ultimately, the requirements for an above-water ocean color radiometer should ensure that the water-leaving radiance $L_w(\lambda)$ from above-water radiometry exhibits uncertainties equivalent to those characterizing in-water measurements of $L_u(z,\lambda)$.

The specifications are applicable to multispectral radiometers equipped with interference filters, and to hyperspectral radiometers based on dispersive devices (e.g., gratings) or monochromators. Minimum performance characteristics are provided for spectral resolution, radiometric responsivity and resolution, signal-to-noise ratio (SNRs), radiometric saturation and minimum detectable values, angular response, linearity, and stability.

2 SPECTRAL AND RADIOMETRIC CHARACTERISTICS

Spectral Characteristics

The nominal spectral bands for current ocean color sensors are detailed in Table 1.1 by aligning the different rows to highlight overlapping bands.

Ideally, field radiometers should provide validation data at the specific satellite bands in the visible spectral range. However, with a few exceptions (e.g., in the case of above-water radiometry over extremely turbid waters), it is recognized that it is difficult to produce reliable in situ data beyond 700 nm with current technology and measurement methods.

Measurement of in situ radiometric quantities in the same spectral bands of satellite sensors requires complying with the spectral specifications given in Table 1.1. Either this presumes performing radiometric measurements with filter radiometers which match the spectral bands of the satellite sensors, or alternatively with hyperspectral radiometers having spectral resolution high enough to allow accurate reconstruction of the satellite signal through spectral convolution.

Filter radiometers should ideally have all the satellite spectral bands as defined by center wavelengths and full-width at half-maximum (FWHM) bandwidths. This implies the use of properly blocked interference filters ensuring the required spectral bandpass and out-of-band rejection (10^{-4} or better of the normalized peak transmittance). Extra care must be taken to avoid possible out-of-band leakage due to fluorescence by the materials constituting the filter or any other optical component.

The center wavelength and bandwidth of filter radiometers should be determined on the assembled instrument. Defining a desirable ±2 nm uncertainty for the center wavelength of a 10 nm FWHM filter installed in a radiometer, this requirement can be satisfied using filters with ±1 nm center wavelength uncertainty and 8.5 ± 1 nm FWHM bandwidth. In fact, when filters are installed in a radiometer with a 20° full-angle FOV, the spectral bandpass is broadened by –a few nm (McCluney 1994) and the center wavelength is also shifted. Furthermore, as filters age in use, their transmission curve may undergo changes further broadening the FWHM bandpass and shifting the peak. Thus the tolerances indicated above include an allowance for some degradation. In a single instrument system comprising multiple filter radiometers (measuring $E_s(\lambda)$, $E_d(\lambda)$, $E_u(\lambda)$, and/or $L_u(\lambda)$), it is desirable that all channels at a given nominal wavelength match within 1 nm. This would imply all filters at any nominal center wavelength are from a single manufacturing lot. If this is accomplished, all the radiometric quantities measured with such a system would have a greater likelihood of having matching spectral bands. In any event, the actual spectral response function of each radiometer band should be characterized with an uncertainty of 0.2 nm.

Table 1.1: Spectral bands of current satellite ocean color sensors. Note that either the validation of radiometric data products or the indirect calibration (i.e., system vicarious calibration (SVC)) of the satellite sensor for center wavelengths greater than 700 nm, in general, is not performed relying on in situ radiometry.

MODIS bands [nm]	VIIRS bands[1] [nm]	OLCI bands[2] [nm]
		400 (15)
405-420	402-422	412(10)
438-448	436-454	442 (10)
483-493	478-498	490(10)
		510(10)
526-536		
546-556	545-565	560(10)
		620(10)
662-672	662-682	665(10)
673-683		674(7.5)
		681(7.5)
		709(10)
743-753	739-754	754(7.5)
		779(15)
862-877	846-885	865(20)
		940(20)
		1020(40)

1. VIIRS bands are specified for S-NPP.
2. OLCI bands are specified as nominal band center and band width.

Table 1.2: Recommended specifications for hyperspectral radiometers applied for validation activities.

Optical Sensors	
Spectral Range:	380 to 900 nm
Spectral Resolution:	3-10 nm (FWHM)
Spectral Sampling:	1-3 nm (or at least 2 times the spectral resolution)
Wavelength Accuracy:	10 % FWHM resolution
Wavelength Stability:	5 % FWHM of resolution
Signal-to-Noise Ratio:	1,000:1 (at minimum)
Stray Light Rejection:	10^{-5} (of the maximum radiometric signal at each spectral band)
FOV Maximum (full-angle):	5°, 20° (for above-water and in-water, respectively)
Temperature Stability:	Specified for 0–45°C
Linearity:	Correctable to 0.1 %

Hyperspectral radiometers based on dispersive elements with spectral resolution of 3-10 nm and spectral sampling of 1-3 nm, are a valuable alternative to filter radiometers and provide high flexibility for a comprehensive validation of data from each visible band of the various satellite ocean color sensors. Hyperspectral radiometers with sub-nanometer spectral resolution, are required for system vicarious calibration (SVC).

Stray light is a major issue affecting hyperspectral systems. Their characterization requires considerable effort to accurately determine the spectral stray light response distribution function across the spectrometer wavelength range. Stray light should be characterized and minimized with maximum residuals below 1% across the full spectral range.

Table 1.2 summarizes recommended specifications for hyperspectral radiometers applicable for validation activities. Requirements for SVC are significantly higher.

Responsivity, Signal-to-Noise Ratio, and Resolution

The expected operating limits for radiometric responsivities, signal to noise ratio (SNR), and digital resolution are specified in Table 1.3 as resulting from the following assumptions and requirements.

1. An E_d and E_s saturation value of 300 μW cm^{-2} nm^{-1} is assumed at all wavelengths, assuming a typical collector diameter of 25 mm or greater. For radiometers with fixed acquisition time on the order of milliseconds, this large saturation value is required to properly deal with in-water downward intense wave focusing events (Zaneveld *et al*., 2001). These events are averaged out in the case of longer integration times. Smaller collectors would require a higher saturation value (Darecki *et al*., 2011).

2. Implicit, but not stated, the minimum required E_s is 20 μW cm^{-2} nm^{-1}. It is considered not appropriate to perform validation stations when illumination is less than this threshold.

3. The minimum E_s implies a minimum detectable E_d(z) value of 1 μW cm^{-2} nm^{-1} at 3 optical depths (i.e., at a depth determined by $3/K_d$).

4. Digital resolution must be less than or equal to 0.5 % of the reading to maintain a very minimum 100:1 SNR. To permit an ideal target of 1 % uncertainty in absolute calibration, the instrument must digitally resolve 0.1 % of the irradiance (radiance) produced by the laboratory standards used. The "Calibration Irradiance (Radiance)" and related "Digital Resolution (Irradiance or Radiance cal.)" provided in Table 1.3 are for typical irradiance (radiance) values applied during calibrations performed with 1000 W FEL irradiance standard lamps traceable to National Measurement Institutes (NMIs). A SNR of 100:1 requires a resolution in $E_d(z)$ at three optical depths to 0.005 μW cm^{-2} nm^{-1} per count. At the surface, $E_d(0)$ or E_s should be resolved to within 0.05 μW cm^{-2} nm^{-1} per count.

5. The Case-1 saturation values of $E_u(0)$ are estimated for the maximum reflectance expected in ordinary Case-1 waters: 12.5 % at 410 nm, 7.5 % at 488 nm and 0.5 % at 670 nm (Mueller and Austin 1992). These saturation values are too low for measurements in Case-2 waters, or coccolithophorid blooms. In these conditions, a maximum expected reflectance of 40 % for $\lambda < 660$ nm and 20 % for $\lambda \geq 660$ nm is assumed. This implies that the expected maximum irradiance in $E_u(0)$ should be 120 μW cm^{-2} nm^{-1} for $\lambda <660$ nm and 60 μW cm^{-2} nm^{-1} for $\lambda \geq 660$ nm.

6. The minimum required irradiance at three optical depths assumes a minimum reflectance of 1 % at 410 nm, 2 % at 488 nm, and 0.15 % at 670 nm.

7. The saturation and minimum radiances, and the related radiance responsivity resolutions for $L_u(0)$ and $L_u(3/K_d)$ are calculated as $L_u/E_u = Q^{-1}$ times the corresponding specification for $E_u(0)$ or $E_u(z)$. Mueller and Austin (1995) assumed $Q = 5$, constant at all wavelengths and depths. Morel and Gentili (1996) showed that Q actually varies between approximately 3.14 and 5 at 410 nm and 488 nm, and between approximately 3.14 and 5.7 at 670 nm. Saturation radiances, for the extreme minimum case of $Q = 3.14$ (very clear waters with the sun nearly overhead), are increased by a factor of 1.6 at all three wavelengths relative to Mueller and Austin (1995). Minimum radiances at 670 nm, for the extreme maximum case of $Q = 5.7$ (turbid waters and solar zenith angle > 60^{o}), are decreased by a factor of 0.75, which implies a corresponding change of the digital resolution at 670 nm. Minimum expected radiances and required digital resolution at 410 nm and 488 nm are unchanged.

Table 1.3: Required sensitivities for satellite validation as a function of the radiometric measured variable and sample wavelength.

Property	*Variable*	410 nm	488 nm	665 nm	*Comment*
$E_d(z,\lambda)$,	$E_d(0)_{max}$	300	300	300	Saturation Irradiance
Downwelled	$E_d\left(\frac{3}{K_d}\right)$	1	1	1	Minimum Expected Irradiance
Irradiance	$\frac{dE}{dN}$	5×10^{-3}	5×10^{-3}	5×10^{-3}	Digital Resolution (profiles)
	$\frac{dE}{dN}$	5×10^{-2}	5×10^{-2}	5×10^{-2}	Digital Resolution (surface unit)
$E_u(z,\lambda)$,	$E_u(0)_{max}$	120	120	60	Saturation Irradiance (Case-2/coccoliths)
Upwelled		37	22	1.5	Saturation Irradiance (Case-1)
Irradiance	$E_u\left(\frac{3}{K_d}\right)$	1×10^{-2}	2×10^{-2}	1.5×10^{-3}	Minimum Expected Irradiance
		$5\ 10^{-5}$	$1\ 10^{-4}$	$7.5\ 10^{-6}$	Digital Resolution (profiles)
	$\frac{dE}{dN}$	1×10^{-3}	2×10^{-3}	1.5×10^{-4}	Digital Resolution (surface unit)
$L_u(z,\lambda)$,	$L_u(0)_{max}$	38	38	13	Saturation Radiance (Case-2/coccoliths)
Upwelled		12.0	7.2	0.5	Saturation Radiance (Case-1)
Radiance	$L_u\left(\frac{3}{K_d}\right)$	2×10^{-3}	4×10^{-3}	2.25×10^{-4}	Minimum Expected Radiance
		$1\ 10^{-5}$	$2\ 10^{-5}$	$1\ 10^{-6}$	Digital Resolution (profiles)
	$\frac{dL}{dN}$	2×10^{-4}	4×10^{-4}	2×10^{-5}	Digital Resolution (surface unit)
E_{cal}, Source	E_{cal}	2	5	15	Calibration Irradiance
Irradiance	$\frac{dE}{dN}$	2×10^{-3}	5×10^{-3}	1×10^{-2}	Digital Resolution (E_d, E_s, E_u cal.)
L_{cal}, Source	L_{cal}	0.6	1.5	4.5	Calibration Radiance
Radiance	$\frac{dL}{dN}$	6×10^{-4}	1×10^{-3}	4×10^{-3}	Digital Resolution (L_u cal.)

Notes:
1. E_u and E_d are in units of μW cm^{-2} nm^{-1} and L_u is in units of μW cm^{-2} nm^{-1} sr^{-1}.
2. Responsivity resolution in radiometric units per digital count at the minimum required signal level.
3. Specified ranges should maintain a 100:1 SNR.

The specifications in Table 1.3 are meant as guidance for the implementation and handling of the following performance requirements:

1. The instrument must maintain at least a 100:1 SNR at every operating range encountered during field measurements.
2. The data for measurements obtained in the field must be recorded with a digital resolution less than or equal to 0.5 % of the reading.
3. The dynamic range of the instrument linear sensitivity must include the signal levels encountered during laboratory calibrations, and the calibration signals must be recorded with a digital resolution of at least 0.1 % of reading to permit to support the 1 % ideal target uncertainty in calibration.

In general, the above performance specifications do not create engineering challenges, with the possible exception of the full dynamic range implied by Case-2 or coccolith saturation radiance $L_u(665)$ to minimum expected value in oligotrophic waters. In any event, this requires specially designed radiometers (see also "*Red and Near-Infrared Wavelengths*"). In fact, it is not necessary that every radiometer used for satellite ocean color sensor validation can operate over the full dynamic ranges given in Table 1.3. A radiometer is only required to maintain the above performance specifications over the dynamic ranges of irradiance and radiance existing at locations and associated illumination conditions where it is operated.

Red and Near-Infrared Bands

The fact that red and near-infrared bands between approximately 700 nm and 900 nm have such short attenuation lengths in water requires that special attention be paid to measurements. In fact, instrument self-shading (Gordon and Ding 1992) and very rapid attenuation of $L_u(z,\lambda)$ make radiometers with large diameter and large system packages, ill suited for these measurements. Additionally, $L_W(\lambda)$ from above-water radiometry is largely affected by uncertainties due to sky-glint correction. Thus, fiber optic probes carrying light back to a remote instrument (Yarbrough, *et al*. 2007), or very small single-wavelength discrete instruments, both combined with small floating platforms, are likely the sole alternative allowing to extend radiometric measurements in the near-infrared. Still, care must be taken to avoid direct shading by the deployment platform, even though at these wavelengths the large attenuation coefficient of water makes irrelevant any shadowing by objects more than a few meters away.

The minimum measurement scheme should include two discrete (e.g., 10 nm FWHM) channels at 780 nm and 875 nm. Additional channels at 750 nm and 850 nm hopefully supported by high-spectral resolution radiometry, would be useful in determining the spectral distribution of the upwelling light field in these spectral regions. Obviously, when in-water measurements are performed at these bands, the E_s sensor should also include the same bands.

The previous in-water measurements, because of their importance in the atmospheric correction algorithms, should be performed in cases of extremely high productivity or in coccolithophorid blooms. It is anticipated that in the majority of cases, and particularly in Case-1 waters, these measurements will show negligible upwelling light.

Polarization Sensitivity

Radiometers may exhibit sensitivity to polarization. In particular, polarization sensitivity is likely to affect any radiometer having mirrors, prisms or gratings in its optical path. Still, the problem is generally of relevance only for radiance measurements because diffusers, constituting the fore optics of irradiance sensors, act as depolarizers. For radiance measurements, the polarization sensitivity must be decreased to values of less than 1% in all bands by depolarizing the aperture radiance either through fiber optics or a *pseudo-depolarizer*. Obviously, an exception is provided by those radiometers designed to actually measure the polarization components of the radiance (e.g., Fougnie *et al* 1999).

3 ADDITIONAL CHARACTERISTICS

Linearity and Stability

The combined uncertainties attributable to linearity and stability should be well below 0.5 % of the instrumental readings over the dynamic ranges specified in Table 1.2, although the actual dynamic range required is significantly lower. This is a challenging goal, but one of those that must be met if the equally challenging goal of achieving the ideal target of 1% uncertainty in absolute calibration is to be meaningful.

Angular Response

Irradiance: The response of a *cosine collector* to a collimated light source incident at an angle θ from the normal must be such that:

1. for E_u measurements the integrated response to a radiance distribution of the form $L(\lambda,\theta) \propto 1+4\sin\theta$ should vary as $\cos\theta$, within 2 %;
2. for E_d measurements, the response to a collimated source should vary as $\cos\theta$ within less than 2 % for angles $0 \le \theta \le 65°$ and 10 % for angles $65° \le \theta < 90°$; and
3. for E_S measurement the response to a collimated source (in air) should match cos θ within a target value of 1 % for $0 \le \theta \le 65°$, and within 5 % for $65° \le \theta < 90°$.

Departures from $\cos\theta$ translate directly to approximately equal errors in E_s or near surface E_d in the case of direct sunlight.

Radiance: The in-water full-angle FOV for the upwelling radiance bands should be smaller than 20°. The resulting solid angle FOV (approximately 0.1 sr) is large enough to provide reasonable levels of flux using silicon detectors, yet small enough to be unaffected by the small angular variations characterizing the upwelling radiance at nadir. Smaller FOV sensors are appropriate, of course, if all of the other performance specifications are satisfied.

The full-angle FOV of above-water radiometers applied for L_T and L_i measurements should tentatively be lower than 5°, and all bands must be co-registered to within a high portion of the FOV.

Operating Depths and Accuracy

Instruments used for profiling in clear to moderately turbid waters shall be capable of operating to several tens of meters depth. Instruments used for profiling in very turbid waters require a much lower maximum pressure rating.

The accuracy required for depth measurements can be determined by relating it to the uncertainty induced in propagating the measurement to the surface. With a desired target of 1%, the upper level of the required measurement accuracy can be given by $\ln(1.01)/K_{\Im}$, where $K_{\Im}$ is the diffuse attenuation coefficient for the specific radiometric quantity $\Im$ (e.g., E_d). For example, in clear water, in the blue bands where $K_{\Im}$ may reach values as low as 0.03 m^{-1}, this requirement is not stringent, in fact it leads to an uncertainty on the order of 0.3 m. For more turbid waters, or in the red bands, were $K_{\Im}$ can be on the order of 0.5 m^{-1}, the required uncertainty is much more stringent and approaches 0.02 m.

Instrument Attitude

The orientation of the instrument with respect to the vertical shall be generally within ±5° and the attitude shall be measured with orthogonally oriented sensors from 0-30° with an uncertainty better than 0.5°. It is not intended that this uncertainty is maintained while the instrument is subject to large accelerations induced by surface waves.

Due to the high accuracy requirements, only E_s field measurements exhibiting tilt within ±2° should be retained for successive processing.

Time Response

The time response of the instrument to a full-scale step change (saturation to dark) in irradiance or radiance, should be less than one second to arrive at a value within 0.1 %, or one digitizing step, whichever is greater, of steady state. In addition, the electronic *e*-folding time constant of the instrument must be consistent with the rate at which the channels are sampled, *i.e.*, if data are to be acquired at 10 Hz, the *e*-folding time constant should be 0.2 s to avoid aliasing.

4 FUTURE DIRECTIONS

Attention should be given to requirements and specifications for measurements in the ultraviolet bands incorporated in forthcoming ocean color missions. Additionally, requirements for polarized radiometers should be considered. Finally, because of the increasing use of hyperspectral systems for both above- and in-water measurements, more detailed specifications should be determined accounting for spectral response differences of silicon detector arrays across the visible spectral region.

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Chapter 3: Calibration and Characterization of Optical Radiometers

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1 INTRODUCTION

Procedures for calibrating and characterizing optical radiometers, including the determination of characteristics peculiar to underwater sensors, are presented in this chapter. The characterizations are considered essential to verify the compliance with specifications of those radiometers used to acquire field data for satellite ocean color validation. Both calibrations and characterizations are those required to determine:

1. Spectral radiometric responsivity (i.e., absolute response) traceable to National Measurement Institutes (NMI) standards;
2. Spectral response functions (i.e., bandpass) of the various radiometer bands;
3. Out-of-band response and stray light perturbations;
4. Responsivity change with the refractive index of the medium in which the radiometer operates;
5. Angular response, both in air or in water, depending on the medium in which the radiometer operates;
6. Linearity of response;
7. Integration time response;
8. Temperature response;
9. Polarization sensitivity;
10. Sensitivity decay;
11. Temporal response;
12. Pressure effects.

Any field instrument providing suitable data for satellite validation should have a traceable history of calibrations and characterizations. In particular, spectral responsivity should be performed before and after each major field deployment. Conversely, certain characteristics such as the angular response only need to be determined once (unless the instrument is modified). Further, among the different characterizations, some should be performed for each individual instrument such as the determination of the immersion factor of irradiance sensors. Others, such as linearity response, may be able to be confidently applied for each class of radiometers (i.e., those made of identical components for which it was proven that specific optical characteristics exhibit equivalent features within a given uncertainty). Table 1.1 summarizes instrument-specific calibrations and characterizations to be performed regularly (i.e., regular), occasionally (occasional) and tentatively once (initial), and those not strictly instrument-specific which can rely on characterizations performed for radiometers of the same class (class-based).

2 RADIOMETRIC RESPONSIVITY

The determination of the absolute radiometric response (i.e., responsivity) of irradiance and radiance sensors requires the availability of a properly furnished and manned calibration facility. Such a facility must be equipped with suitable stable sources, *e.g.*, lamp standards of spectral irradiance calibrated by NMIs. The facility must also have a variety of specialized radiometric and electronic equipment, including: reflectance plaques, spectral filters, integrating spheres, and highly regulated power supplies for the operation of lamps. Precision electronic measurement capabilities are also needed, both for setting and monitoring lamp current and voltage.

Instrument manufacturers and a few research laboratories are equipped and staffed to perform these calibrations for the ocean color research community. These facilities should perform frequent intercomparisons to ensure maintenance of the radiometric traceability to NMI standards. An ambitious goal is to perform calibrations from 350 nm to 900 nm with 1 % target uncertainty for irradiance and slightly higher for radiance.

Table 1. Basic requirements on the type and occurrence of calibrations for the main characterizations of field radiometers supporting ocean color validations activities.

	Regular	Occasional	Initial	Class-based
Radiometric responsivity	X			
Spectral response		X		
Out-of-band & stray-light		X		
Immersion factor (irradiance)			X	
Immersion factor (radiance)				X
Angular response			X	
Linearity				X
Temperature response				X
Polarization sensitivity				X
Temporal response				X
Pressure effects				X

The main standards used for irradiance responsivity are FEL lamps[1] having assigned scales of spectral irradiance that have been transferred directly, or indirectly via secondary standards, from the scales of radiometric standards maintained by NMIs. The spectral irradiance scales of the FEL lamps are in turn transferred to spectral radiance scales using plaques of known bidirectional reflectance, or integrating spheres, or both.

[1] "FEL" is a commercial lamp-type designator. The 1000 W FEL lamps used for spectral irradiance calibration are modified by welding on a special base, which has much larger terminals than are provided with the stock commercial bulbs (Walker *et al.* 1987). Following this modification, the spectral irradiance output of each lamp is scanned with a high-resolution monochromator, to assure that its spectrum is smooth and free from unwanted emission lines. Finally, the candidate calibration source lamp is "seasoned" by initially burning it for approximately 24-hours, using a highly regulated current source; its spectral irradiance output and lamp terminal voltage are carefully monitored. Lamps that do not achieve stable performance during the seasoning process are discarded. Several commercial vendors offer both seasoned FEL lamps, and seasoned lamps with a certified scale of spectral irradiance transferred from another FEL secondary standard lamp acquired directly from NMI.

The SeaWiFS (Sea-Viewing Wide Field-of-View Sensor) Project Office initiated a series of SeaWiFS Intercalibration Round-Robin Experiments (SIRREXs) to assure internal consistency between the laboratories calibrating radiometers for SeaWiFS validation (Mueller 1993 and Mueller *et al*. 1994). The outcome from SIRREX-3 (Mueller *et al*. 1996) and SIRREX-4 (Johnson *et al*. 1996), showed that with properly maintained FEL lamp secondary and working standards, thorough training of laboratory personnel and careful attention to measurement setups, it is possible to maintain an uncertainty level below 2 % for spectral irradiance and 3 % for spectral radiance calibrations. Successively, round-robin comparisons of calibration coefficients determined for a reference set of field instruments were implemented to benchmark the internal consistency of calibrations performed at various labs. In particular, SIRREX-6 showed a level of relative uncertainty of approximately 2% across the involved laboratories (Riley and Bailey, 1998). Following this work, a new series of round-robin comparisons called SIMBIOS Radiometric Intercomparison (SIMRIC) based on a transfer radiometer (i.e., the SeaWiFS Transfer Radiometer (SXR)) directly calibrated by NIST (Johnson *et al.* 1998), were used to compare the radiance scales of the calibration sources at the various laboratories (Meister *et al*. 2002). Results showed that laboratory and SXR scales agreed within approximately 2 % for most spectral bands considered (Meister *et al*. 2002).

The above results clearly indicate some common calibration traceability must exist. In particular, multiple facilities (e.g., instrument manufacturers, and some research labs or government institutions) should make their standards and protocols directly traceable to NMI scales (Johnson *et al*. 1996). As an example, figure 1 shows the schematic of such an organizational structure established within the framework of the SIMBIOS Project.

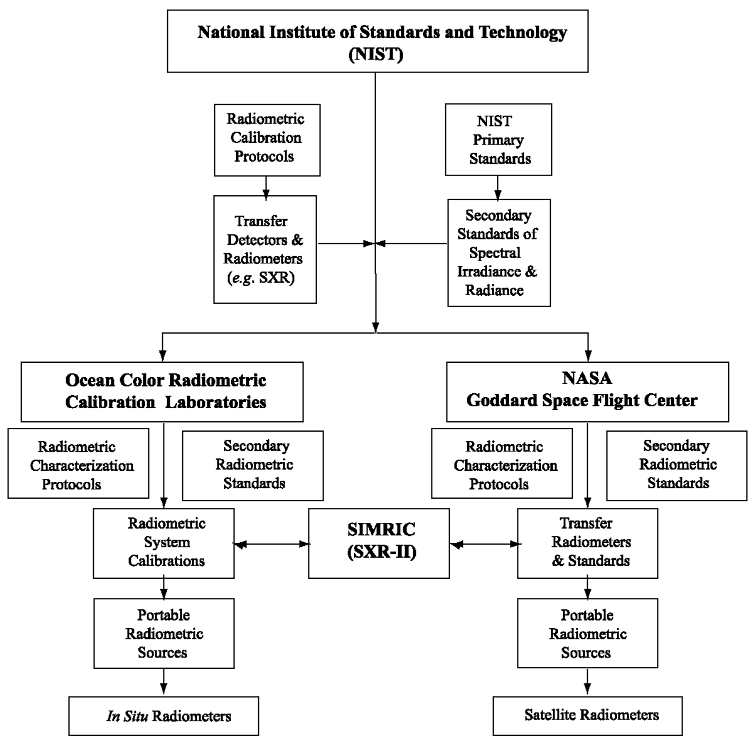

Figure 1: Organizational structure for radiometers characterization and calibration established by the ocean color research community within the framework of SIMBIOS Project.

Spectral Irradiance Calibration

Radiometric calibrations of irradiance sensors can be performed after ascertaining: conformity of the sensor angular response to the required cosine function, sensor linearity, spectral sensitivity, and also satisfactory out-of-band blocking or low stray light perturbations.

As already mentioned, radiometric calibrations mostly rely on FEL lamp standards of spectral irradiance. These lamps can be provided by NMIs (e.g. NIST, NPL) as secondary standards with NMI-traceable spectral irradiance scales. Alternatively, they are available as working standards (i.e., with calibrations traceable to a secondary standard) from various commercial laboratories and manufacturers. The expanded combined uncertainty (corresponding to a coverage factor k=2 indicating a 95% confidence level) of a NIST-issued secondary standard FEL is approximately 1.1 % to 1.6 % in the ultraviolet and 0.5 % to 0.6 % in the visible and near-infrared (Yoon *et al*. 2003).

NIST has delivered guidelines for the setup, alignment, and use of FEL lamp standards (Walker *et al.* 1987). Additional user guidelines have been issued by vendors who manufacture and calibrate these lamps. The irradiance calibration procedure (Walker *et al.*, 1987; Johnson, *et al.* 1996) is summarized as follows:

- The irradiance sensor and a suitable fixture for the FEL lamp are mounted on an optical bench. The lamp space must be appropriately baffled and draped so that occulting the direct path between lamp and sensor results in a response of less than 0.1 % of the unocculted signal. Best practice suggests the lamp and sensor are operated in separate spaces (e.g., rooms) with a variable sized aperture to confine the lamp flux near the edges of the irradiance collector. The size of the aperture, however, should be large enough to prevent diffractive fringes affecting the irradiance collection area. Curtains and partitions offer an alternative solution to baffle the light source. Regardless of how the baffling is accomplished, the most critical aspect is to eliminate on-axis reflections, *e.g*. as might result from a flat surface directly behind the lamp and perpendicular to the optical axis (Walker *et al*., 1987). The alignment reference target for FEL lamps, i.e., an alignment jig made of a window with cross hairs etched to mark the location of the lamp filament, is mounted in the lamp holder.
- An alignment laser beam is directed normal to the target window. The alignment is achieved when the retro-reflection from the window is directed back on the laser aperture.
- The sensor is mounted on the optical bench with the irradiance collector centered on the alignment laser beam, which marks the optical axis. The collector is aligned normal to the beam using a mirror held flat against the collector to reflect the beam back through the lamp-target cross hairs to the laser aperture.
- The distance r along the optical path between the collector surface and the terminal posts of the lamp alignment jig is accurately measured. The standard reference distance for all NMI traceable FEL lamp scales of spectral irradiance is $r = 50.0\text{ cm}$.
- The FEL lamp spectral irradiance standard is inserted into the lamp-holder with its identification tag facing away from the sensor. The lamp terminals are connected to a current-regulated, direct current power supply, with careful attention to ensure proper polarity (as marked on the lamp). The power supply is turned on and ramped-up to the proper current for the particular lamp (as specified within the lamp calibration certificate). A shunt and a voltmeter with an appropriate number of digits should be used to monitor the lamp current to the nearest 0.001 A. Following a 15-30 min warm-up, irradiance calibration measurements can be taken. The voltage present across the lamp terminals should be measured at frequent intervals during each calibration run, and compared to the voltage measured when the lamp was calibrated (as detailed in the calibration certificate). A significant change in the lamp operating voltage at the specified current indicates that the irradiance output of the lamp has probably changed and that the lamp is no longer usable as a standard of spectral irradiance. It is anticipated that on completion of the calibration session, the lamp current should be ramped down to avoid thermally shocking the filament.
- An occulting device (e.g., a rod) is placed to obstruct the direct optical path between lamp and collector, then the sensor response $DN_{\text{amb}}(\lambda)$ to ambient light is recorded in digital counts. If the ambient response is appreciably higher than the dark response $DN_{\text{dark}}(\lambda)$ measured with the

collector completely covered, then the baffling of the calibration setup is inadequate and should be improved.

- The occulting device is removed from the optical path and the irradiance sensor response $DN_{\mathrm{r}}(\lambda)$ is recorded. The sensor irradiance responsivity calibration factor $F_{\mathrm{E}}(\lambda)$ in air for each band identified by the wavelengths λ, is determined as

$$F_{\mathrm{E}}(\lambda)=\frac{E_{\mathrm{r}}(\lambda)}{DN_{\mathrm{r}}(\lambda)-DN_{\mathrm{amb}}(\lambda)}. \quad [\mu\mathrm{W\ cm^{-2}nm^{-1}counts^{-1}}] \tag{1}$$

If the lamp is at the standard distance $r=50.0$ cm, $E_r(\lambda)=E_{50}(\lambda)$, where $E_{50}(\lambda)$ is the certified NMI-traceable scale of spectral irradiance rigorously determined at 50 cm. The spectral irradiance responsivity coefficients can then be applied to in situ radiometric measurements $DN(\lambda)$ to compute the related irradiance $E(\lambda)$ as

$$E(\lambda)=F_{\mathrm{E}}(\lambda)\left[DN(\lambda)-DN_{\mathrm{dark}}(\lambda)\right], \quad [\mu\mathrm{W\ cm^{-2}nm^{-1}}] \tag{2}$$

where $DN_{\mathrm{dark}}(\lambda)$ is the radiometer dark signal as determined in the field with the aperture capped.

- If the irradiance sensor saturates when it is illuminated by the lamp at the standard distance of 50 cm, it is necessary to reduce the irradiance level by increasing the distance *r*. The corresponding irradiance scale $E_{\mathrm{r}}(\lambda)$ is then determined as

$$E_{\mathrm{r}}(\lambda)=E_{50}(\lambda)\frac{(50+\Delta f)^2}{(r+\Delta f)^2}, \quad [\mu\mathrm{W\ cm^{-2}nm^{-1}}] \tag{3}$$

where Δf is the distance offset between the actual reference plane of the lamp filament and the front plane of the terminal posts. The magnitude of this offset is typically $\Delta f \approx 3$ mm (Biggar 1998), but it may vary among FEL lamps. The value of Δf can be determined for a particular lamp by measuring the irradiance sensor response with the lamp positioned at 50 cm and additionally at a series of *N* distances r_n between 50 cm and, for instance, 300 cm. Assuming that the response of the sensor is linear

$$\frac{DN_n(\lambda)-DN_{\mathrm{amb}}(\lambda)}{DN_{50}(\lambda)-DN_{\mathrm{amb}}(\lambda)}=\frac{(50+\Delta f)^2}{(r_n+\Delta f)^2}. \tag{4}$$

The solution to Eq. 4 at each distance r_n and center wavelength λ of each spectral band is

$$\Delta f_{n,\lambda}=\frac{X_{n,\lambda}\cdot r_n-50}{1-X_{n,\lambda}} \tag{5}$$

where $X_{n,\lambda}\equiv\left\{\left[DN_n(\lambda)-DN_{\mathrm{amb}}(\lambda)\right]/\left[DN_{50}(\lambda)-DN_{\mathrm{amb}}(\lambda)\right]\right\}^{\frac{1}{2}}$.

The filament offset may then be computed as the average of the offsets determined at *N* distances times the number of bands.

When a diffuser collector is used, in addition to the lamp filament offset Δf, the denumerator of Eq. 4 should also take into account the effective distance Δ*d* within the diffuser material representing its reference collection plane (which may vary with wavelength). Further, Eq. 4 is only valid for ideal point sensor and source. Deviation from such an ideal condition would then require applying correction models accounting for the equivalent size of lamp and collector aperture (Manninen *et al.* 2008). Thus, accounting for the previous elements

$$E_r(\lambda) = E_{50}(\lambda)\frac{(50+\Delta f)^2 + r_s^2 + r_d^2}{(r+\Delta f+\Delta d)^2 + r_s^2 + r_d^2}, \qquad [\mu\text{W cm}^{-2}\text{nm}^{-1}] \qquad (6)$$

where r_s and r_d are the equivalent radii of the source and collector aperture.

Spectral Radiance Calibration

Radiance responsivity calibration requires a uniform and near-Lambertian source of known radiance that fills the field-of-view (FOV) of the sensor. The two procedures that are most frequently used to calibrate ocean color radiance sensors are given below.

1. *Reflectance Plaque Radiance Calibration:* A FEL lamp standard of spectral irradiance is used at a distance r, to illuminate a plaque of near-Lambertian reflectance with a known bidirectional reflectance distribution function (BRDF) $\rho(\lambda,\theta_o,\theta)$ calibrated for normal incidence illumination, i.e., $\theta_o = 0$, and a viewing angle $\theta = 45°$. The setup is then identical to that described for *Spectral Irradiance Calibration*, with the reflectance plaque in place of the irradiance collector. All of the above comments pertaining to effective baffling, and determination of the lamp filament offset, apply to this calibration procedure as well. The procedure (see also Johnson *et al.* 1996) is summarized as follows:

   - The alignment of the lamp optical axis normal to the center of the reflectance plaque is best done using an alignment laser, a FEL alignment jig and a mirror placed against the plaque surface at its center, and adjusting the apparatus to achieve retro reflection of the laser beam from both the FEL target and plaque alignment mirror.
   - The FEL standard lamp is positioned on an axis normal to the center of the plaque at distance r. To assure a better uniform illumination across the surface of the plaque, r must typically be greater than 1.5 m. This minimizes the impact of inhomogeneity of the light projected on the plaque (Hooker *et al.* 2002).
   - The filament offset Δf may be determined by the method described for *Spectral Irradiance Calibration.* If this is done using measurements at varying distances with Eq. 5, the FOV of the radiance sensor must be small enough to subtend an area of diameter of a very few centimeters (tentatively 5 cm or less) located at the center of the plaque. If a larger area of the surface is viewed, changes in the spatial distribution of illumination by the FEL may be confounded with the systematic variation associated with the filament offset. It is recommended that, still ignoring the non-ideal point source, a default $\Delta f \simeq 3$ mm (Biggar 1998), or an improved one locally determined including both FEL and plaque specific contributions, is applied for radiance calibrations (Meister *et al.* 2002).
   - The radiance sensor is positioned to view the plaque at an angle $\theta = 45°$ measured from the plaque normal. Other angles at which the diffuse reflectance of the plaque is known are in principle acceptable. It must be established, however, that the plaque fills the sensor FOV and that the presence of the sensor case does not perturb the irradiance on the plaque. The angular alignment of the instrument aperture can be done by rotating the plaque about its vertical axis by 22.5° (measured with an indexing column) and adjusting the instrument to achieve retroreflection (see, Meister *et al.* 2002).
   - The lamp flux is carefully occulted to record the sensor ambient response $DN_{\text{amb}}(\lambda)$. As opposed to the case of *Spectral Irradiance Calibration*, requiring the strict occultation of the flux along the sole optical path between lamp and collector, radiance calibration requires that any flux contribution reaching the plaque directly from the lamp is occulted. Finally, the occulter is removed and the response $DN_r(\lambda)$ to radiance reflected from the plaque is recorded.

- The radiance reflected by the plaque and viewed by the sensor in this geometry is determined as

$$L(\lambda)=\frac{1}{\pi}\rho(\lambda,0°,45°)E_{\mathrm{r}}(\lambda), \tag{7}$$

where the spectral irradiance $E_{\mathrm{r}}(\lambda)$ is calculated using Eq. 3.

2. *Integrating Sphere Radiance Calibration:* An alternative approach to calibrating radiance sensors is to view an integrating sphere that is uniformly illuminated by stable and appropriately baffled lamps, with an exit port large enough to completely fill the sensor FOV. Also, sphere and exit port must be large enough to place the radiance sensor at a distance preventing any significant secondary illumination of the sphere internal walls due to reflections off the sensor entrance optics. In fact, if the sensor is too close, the reflected light increases and distorts the uniformity of the radiance distribution within the sphere. The spectral radiance scale of the integrating sphere can either be determined by an NMI calibration or transferred from the spectral irradiance scale of a FEL lamp standard[2] using the following procedure (Johnson *et al.* 1996):

- An irradiance scale transfer radiometer, configured with an integrating sphere having a circular entrance aperture of radius r_2 as its cosine collector, is calibrated using an FEL standard of spectral irradiance by the method outlined for the *"Spectral Irradiance Calibration"*.
- The irradiance scale transfer radiometer is positioned with the entrance aperture of its integrating sphere collector parallel to and centered coaxially at a distance *d* from the circular aperture with radius r_1 of the integrating sphere.
- The spectral irradiance $E(d,r_1,r_2,\lambda)$ of the integrating sphere exit port is measured using the irradiance scale transfer radiometer, taking care to subtract the ambient light collected with the source exit port occulted.
- Assuming a uniform radiance distribution within the sphere exit port, the spectral irradiance scale of the integrating sphere (Johnson *et al.* 1996) is calculated as

$$L(\lambda)=\frac{E(d,r_1,r_2,\lambda)\cdot(d^2+r_1^2+r_2^2)}{\pi\cdot r_1^2}(1+\delta+\delta^2+\ldots), \tag{8}$$

where $\delta=r_1^2r_2^2\left(d^2+r_1^2+r_2^2\right)^{-2}$.

- Finally, the radiance sensor to be calibrated is positioned in front of the sphere to view the center of the aperture. Its response $DN_{\mathrm{r}}(\lambda)$ is then recorded.

In either approach, the radiance responsivity calibration coefficients of the field radiometer are determined as

$$F_{\mathrm{L}}(\lambda)=\frac{L(\lambda)}{DN_{\mathrm{r}}(\lambda)-DN_{amb}(\lambda)}. \qquad [\mu\mathrm{W\ cm^{-2}nm^{-1}sr^{-1}counts^{-1}}] \tag{9}$$

where $DN_{amb}(\lambda)$ is the laboratory ambient reading.

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[2] In some laboratories, the radiance scale of a sphere is assumed constant for relatively lengthy periods of time between infrequent scale transfers from an FEL source. Often, these laboratories rely on monitoring the sphere output with detectors at one or more wavelengths. A single wavelength monitor can give a misleading impression of sphere stability, however, as patterns of degradation in sources and optical coatings are often highly wavelength dependent (J. Butler and G. Meister, Pers. Comm.).

The radiance from in situ measurements $DN(\lambda)$ is then computed as

$$L(\lambda) = F_L(\lambda)\left[DN(\lambda) - DN_{dark}(\lambda)\right]. \qquad [\mu W\ cm^{-2} nm^{-1} sr^{-1}] \qquad (10)$$

where $DN_{dark}(\lambda)$ is the radiometer dark signal determined in the field with the aperture covered.

4 SPECTRAL CHARACTERIZATION

Spectral characterization aims to determine the spectral response functions of each band, and additionally determining the out-of-band response of filter-radiometers, or stray light in hyperspectral radiometers. These characterizations require that the sensor aperture is filled by a monochromatic source. In the case of radiance sensors, a diffuser placed in front of the optical window can be used to uniformly fill the instrument FOV.

Spectral Response Function

Center wavelengths and bandwidths of each band are required characterizations for any radiometer. These are determined by measuring the spectral response function, *i.e.,* the passband, for each channel with a scanning monochromatic source exhibiting a bandwidth tentatively less than 0.2 nm. For convenience, response functions are commonly normalized to the maximum value. The (nominal) center wavelength is then defined as the wavelength halfway between those at which the normalized response is 0.5. Similarly, the bandwidth is defined as the passband determined by the full-width at half-maximum (FWHM) intensity points.

It is mentioned that detailed knowledge of spectral response functions is essential for accurate radiometric products requiring the convolution of quantities such as the extra-terrestrial solar irradiance in the spectral bands.

It is recommended that the internal instrument temperature be monitored during these characterizations, and that they are repeated at two temperatures at least 15 ^{o}C apart, e.g., 10 and 25 ^{o}C. If a shift with temperature greater than 1 nm is detected for either the center wavelength or bandwidth, additional temperature calibration points (i.e., close to 0 and to 40 ^{o}C) are recommended.

Out of Band Response

Monochromator-based spectral characterizations are not able to adequately measure leakage of broadly distributed out-of-band radiation, but out-of-band radiation can have a significant impact during both calibration and field operation of the radiometers. During calibration, because the calibration sources typically have much more flux in the red then the blue, the concern is out-of-band long wavelength light leaking into the shorter wavelength channels. In the field, particularly for the radiometers viewing the surface, or in the water, the problem is more flux in the shorter wavelengths, and shorter wavelength light leaking into the longer wavelength channels. Thus, the out-of-band blocking of the radiometers must be routinely tested.

In the case of blocking of blue light for bands with center wavelengths longer than 540 nm, where continuous wave argon lasers are available, out-of-band response can be measured at 488 nm. One recommended test that can be performed during absolute calibrations at center wavelengths lower than 640 nm, is the sequenced measurement of three Schott BG-18 filters, each 1 mm thick, using an FEL lamp source. The procedure is to measure the channel signal using each filter separately, then in combination, and comparing the transmissions. If a significantly higher combined transmission of the three filters (when they are used in combination) is measured relative to the calculated transmittance from measurements performed with individual filters, then spectral leakage is present. At center wavelengths greater than 640 nm, other filters that attenuate the wavelength of interest, with a transmission value of less than or equal to 0.1 and which pass shorter wavelength light with significantly greater transmission, should be substituted for the BG-18.

In the case of blocking red light, a convenient way to measure the leakage is to place a long wavelength-pass, sharp-cut, absorbing glass filter that does not exhibit fluorescence between a broadband (e.g., incandescent) source and the sensor. A non-zero response indicates unwanted out-of-band red response and the need for an improved red blocking.

Consideration must also be given to unblocked fluorescence by filters or any other optical component, as an additional possible source of light. Methods to test for fluorescence contamination specifically are not well established at this time.

Stray Light Perturbations

Stray light is a major issue for hyperspectral radiometers. Characterization implies determining the spectral stray light response distribution function across the full spectral range of spectrometers. In recent years these characterizations have been performed with high accuracy by NIST using the Spectral Irradiance and Radiance responsivity Calibrations with Uniform Sources (SIRCUS) system based on integrating spheres illuminated by an ensemble of tunable and fixed frequency lasers covering the visible and near-infrared range (Brown *et al*. 2000). This system was specifically applied to characterize stray light at the 10^{-6} level of the Marine Optical Buoy (MOBY) spectrographs of relevance for SVC (Feinholz *et al.* 2008). Alternative and more affordable stray light characterizations can be performed with monochromators (Talone *et al.* 2016). While the first solution must be applied for each radiometer supporting applications requiring highly accurate measurements (e.g., SVC), the alternative solution is likely applicable for radiometry supporting validation activities.

Common to different characterizations, is the need to fill the entrance aperture of sensors with a pure light source having spectral width much smaller than the sensor bandwidth. This allows determining line spread line functions (LSF) for each band. The inversion of LSF matrices provide basis for stray light corrections (Feinholz *et al.* 2008, Talone *et al.* 2016).

Stray light characterization is a demanding task. Thus, when applicable, class-based characterizations can be considered for commercial instruments used in validation activities.

5 IMMERSION FACTORS

Immersion factors account for responsivity variations resulting from changes in the refractive index of the medium in contact with the fore optics (i.e., the cosine collector and the optical window for irradiance and radiance sensors, respectively).

Immersion Factor for Irradiance Sensors

When a diffuser is immersed in water, its light transmissivity is less than in air. Considering that the instrument irradiance responsivity is determined in air, a correction (i.e., the immersion factor) for the change in transmissivity must be applied to irradiance responsivity coefficients for underwater measurements.

The change in transmissivity of a collector when immersed, is the net effect of two separate processes both depending on the relative difference in refractive indices between the diffuser material (e.g., fused silica, opal glass) and the surrounding medium (i.e., air or water):

1. the first is due to a change in the reflection of light at the external medium-collector interface,
2. while the second is due a change in the reflection of light at the inner collector-medium interface.

The refractive index of the collector material is always larger than that of either water or air, and because the refractive index of water is larger than that of air, the Fresnel reflectance of the water-diffuser interface is smaller than that of the air-diffuser interface. Therefore, the initial transmission of light through the external surface of an irradiance collector is larger in water than in air. Conversely, the inner Fresnel reflectance of the diffuser-water interface is lower than that of the diffuser-air interface. Therefore, a larger fraction of the light scattered within the diffuser and of the light reflected back by the lower diffuser-air interface in the optics interior, passes back into the water column than would be lost into air. Because of the increased flux leaving the diffuser exceeds the gain in the incoming flux, the net effect of these competing processes is a decrease in the transmissivity of the immersed collector.

Previous investigations have shown that the immersion factors for irradiance collectors must be experimentally characterized. In fact, some manufacturers perform this characterization only for prototypes of a particular collector design and material specification, and successively provide nominal immersion factors for all production radiometers using that collector design. With this respect, Mueller (1995) and Zibordi *et al*. (2004) applied the characterization procedure described below with repeatability better than 1% and observed root-mean-square differences between immersion factors of radiometers from the same series exceeding several percent with values as large as 10 % in some spectral bands.

To measure this effect, a suggested procedure (Aas 1968, Petzold and Austin 1988) is as follows:

- The instrument is placed in a tank of water with the irradiance collector levelled and facing upward.
- A tungsten-halogen lamp with a small filament, powered by a stable power supply, is applied as a light source. The measurement system (lamp, radiometer and water vessel) must be carefully aligned and the distance of the lamp above the surface of the irradiance collector carefully measured. After lamp warm-up, an initial reading is taken in air before the water level in the tank is raised above the dry collector. Lamp voltage and shunt current should be monitored throughout the duration of the characterization to assure a stable output. As a further assurance of lamp stability, the output flux can be continuously monitored with a separate in air irradiance sensor (Zibordi *et al*. 2002).
- The water is raised initially to a carefully measured depth z above the collector surface and the radiometer outputs are recorded for all bands. Achieving a repeatability better than 1 % requires careful attention to the cleanliness of the water and removal of any air bubble from fore optics (Zibordi *et al*. 2002). It is thus recommended that pure water (e.g., Milli-Q by Millipore Corporation) and a relatively small water tank with an efficient internal baffling (Zibordi *et al.* 2002, Hooker and Zibordi 2005) are used.
- The water level is then increased stepwise, *e.g.*, at 5 cm increments, and the instrument responses measured and recorded for each depth z. A maximum water depth of a few tens of cm (e.g., 40 cm) is normally adequate to obtain data covering a sufficient range of responses.
- The water level is then lowered, and data recorded, over a similar series of incremental depths. The lamp and shunt voltages must be regularly recorded to detect changes in the lamp power that may affect the measurement sequence. The water temperature should be also recorded during the measurement sequence to accurately determine the water refractive index.
- A final reading is taken with the water level below the collector after drying it.

A minimum water depth of tentatively 5 cm is recommended to avoid artifacts due to multiple reflections between the collector and water sub-surface. These reflections would artificially increase the transmitted flux, and therefore, decrease the apparent immersion effects. The magnitude of this artifact increases with a decrease in the minimum depth and an increase in the diameter of the collector.

The amount of energy arriving at the collector varies with water depth and is a function of several factors:

1. the attenuation at the air-water interface, which varies with wavelength;
2. the attenuation over the water pathlength, which is a function of depth and wavelength; and

3. the change in solid angle of the light leaving the source and arriving at the collector, caused by the light rays changing direction at the air-water interface, which also varies with wavelength and water depth.

Using the Fresnel reflectance equations, the transmittance through the water surface is

$$T_S(\lambda) = \frac{4n_w(\lambda)}{\left[1 + n_w(\lambda)\right]^2}, \tag{11}$$

where $n_w(\lambda)$ is the index of refraction of the water at wavelength λ.

The change with water depth z of the refracted solid angle subtended by the collector, as viewed from the lamp filament, is given by

$$G(z,\lambda) = \left[1 - \frac{z}{d}\left(1 - \frac{1}{n_w(\lambda)}\right)\right]^{-2}, \tag{12}$$

where *d* is the distance of the lamp source from the collector surface.

The immersion correction factor $F_{i,E}(\lambda)$ for irradiance is then calculated as

$$F_{i,E}(\lambda) = \frac{DN_a(0^+,\lambda)}{DN_w(0^-,\lambda)} T_S(\lambda), \tag{13}$$

where $DN_a(0^+,\lambda)$ and $DN_w(0^-,\lambda)$ are in-air and subsurface irradiances in digital counts corrected for dark signals, respectively. The latter value is determined from the least squares fit as a function of the water depth z_i above the collector of $\ln[DN_w(z_i,\lambda)/G(z_i,\lambda)]$. Where the factor $G(z_i,\lambda)$ corrects for the geometric effects induced by the change in solid angle of the light leaving the source and arriving at the collector.

As already discussed, a high reproducibility of $F_{i,E}(\lambda)$ determinations requires the use of pure water (e.g., Milli-Q). The actual application of derived $F_{i,E}(\lambda)$ values to field measurements, then requires corrections accounting for differences in the refractive indices between pure and natural waters as a function of salinity and likely temperature. Because of the difficulty of generating and working with "pure" seawater, the correction to account for salinity and temperature effects, can only rely on experimental estimates of the correction factor to be applied to the pure water calibration. This approach is not expected to appreciably increase the uncertainty assigned to the experimental determination of $F_{i,E}(\lambda)$.

Immersion Factor for Radiance Sensors

Equivalent to irradiance sensors, the absolute calibration for spectral radiance sensors is performed in air. Thus, when the instrument is submerged in water, a change in responsivity occurs and a correction must be applied. This change in responsivity is caused by

1. a change in transmission through the water-window interface with respect to the transmission of the air-window interface, and
2. a change in the solid angle FOV relative to that in air.

Since $n_w(\lambda)$ is a function of wavelength, the correction factor $F_{i,L}(\lambda)$ is also a function of wavelength. Given that the refractive index of air is 1 at all wavelengths, if $n_g(\lambda)$ is the index of refraction for the material constituting the optical window of the radiance sensor, the correction for the change in transmission through the window, $T_g(\lambda)$, is given by (see Austin 1976)

$$T_{\mathrm{g}}(\lambda)=\frac{\left[n_{\mathrm{w}}(\lambda)+n_{\mathrm{g}}(\lambda)\right]^{2}}{n_{\mathrm{w}}(\lambda)\left[1+n_{\mathrm{g}}(\lambda)\right]^{2}}, \tag{14}$$

and the correction for the change in FOV is

$$F_{\mathrm{v}}(\lambda)=\left[n_{\mathrm{w}}(\lambda)\right]^{2}. \tag{15}$$

For a Plexiglas™ window, the spectral refractive index $n_{\mathrm{g}}(\lambda)$ can be conveniently computed using an empirical fit to the Hartmann formula, as (see Austin 1976)

$$n_{\mathrm{g}}(\lambda)=1.47384+\frac{7.5}{\lambda-174.71}, \tag{16}$$

where λ is in units of nm. For different materials commonly used for optical windows (e.g., BK-7, fused silica) the refractive indices are provided by the manufacturers.

The index of refraction for seawater $n_{\mathrm{w}}(\lambda)$ can be similarly computed using an empirical fit of the data from Austin and Halikas (1976) for pure water at 22 °C (an empirical function for different salinities and temperatures is given in Quan and Fry (1995)), as

$$n_{\mathrm{w}}(\lambda)=1.325147+\frac{6.6096}{\lambda-137.1924}. \tag{17}$$

By combining the corrections $T_{\mathrm{g}}(\lambda)$ and $F_{\mathrm{v}}(\lambda)$, the immersion factor $F_{\mathrm{i,L}}(\lambda)$ for a radiance sensor is given by

$$F_{\mathrm{i,L}}(\lambda)=\frac{n_{\mathrm{w}}(\lambda)\left[n_{\mathrm{w}}(\lambda)+n_{\mathrm{g}}(\lambda)\right]^{2}}{\left[1+n_{\mathrm{g}}(\lambda)\right]^{2}}. \tag{18}$$

This equation ideally applies to Gershun tube radiometers with an optical window as foreoptics. Because of this, efforts were made to experimentally characterize $F_{\mathrm{i,L}}(\lambda)$ for radiometers exhibiting different optical designs (Zibordi 2006, Zibordi and Dareki 2006, Feinholz *et al.* 2017), where the interaction of light with the various components of the optical system may affect the responsivity.

Two experimental methods were proposed and applied to determine $F_{\mathrm{i,L}}(\lambda)$ (see Zibordi 2006 and Feinholz *et al.* 2017). Following the method proposed by Zibordi (2006), the experimental characterization of $F_{\mathrm{i,L}}(\lambda)$ for radiance sensors is made through in–air and in–water radiance measurements successively performed with a constant sensor–source distance and the sensor looking vertically down at a stable, homogeneous and near-Lambertian source virtually immersed in pure water. The measurement procedure is equivalent to that applied for the determination of the *Immersion Factor for Irradiance Sensors*, except that immersed measurements are taken with a single distance r between the optical window and source, while multiple in-air measurements are taken decreasing the water level z_i and thus with diverse water depths r-z_i between water surface and optical window. The diffuse light source can be obtained with an LCD flat-field source (Feinholz *et al.* 2017) operated underneath a water tank with the bottom made of a transparent material (e.g., optical glass), or alternatively a number of quality diffusers illuminated by a halogen tungsten lamp operated at an opportune distance to increase homogeneity of the resulting diffuse source (Zibordi 2006).

Following Zibordi (2006) $F_{\mathrm{i,L}}(\lambda)$ is determined from

$$F_{\mathrm{i,L}}(\lambda)=\frac{DN_{a}(\lambda)}{DN_{w}(0^{-},\lambda)}\frac{\Omega_{a}}{\Omega_{w}(\lambda)}\frac{1}{T_{wa}(\Omega_{w},\lambda)} \tag{19}$$

where $DN_a(\lambda)$ is the digital value related to the above–water radiance corrected for the dark signal. This term is computed as the intercept of the least squares fit — as a function of the distance z_i of the optical window from the water surface — of in–air measurements made with diverse water levels r-z_i. The term $DN_w(0^-,\lambda)$ is the digital value related to the in–water radiance, corrected for the dark signal, measured with the instrument immersed. The terms Ω_a and $\Omega_w(\lambda)$ are the in-air and in-water solid angle field–of–views, respectively (their exact values are not required because their ratio is known, i.e., $\Omega_a / \Omega_w(\lambda) = n_w^2(\lambda)$), while $T_{wa}(\Omega_w,\lambda)$ indicates the water–air transmittance averaged over the solid angle $\Omega_w(\lambda)$.

The experimental characterization of $F_{\mathrm{i,L}}(\lambda)$ for sample radiometers of the same series did not show appreciable sensor-to-sensor dispersion (Zibordi 2006). However, theoretical and experimental determinations exhibited appreciable differences for some radiometer series (Zibordi and Dareki 2006). These findings suggest that *i.* values of $F_{\mathrm{i,L}}(\lambda)$ can be confidently applied to radiance sensors of a given class, still, *ii*. the experimental characterization of $F_{\mathrm{i,L}}(\lambda)$ for sample radiance sensors of each class is desirable to detect differences between theoretical and experimental determinations.

Finally, relative changes of $F_{\mathrm{i,L}}(\lambda)$ as a function of the refractive index of natural waters, can be easily quantified through Eq. 18 as a function of $n_w(\lambda)$ for different temperatures and salinities (Zibordi 2006).

6 ANGULAR RESPONSE

Radiance Field-of-View

The radiance FOV does not normally enter into the absolute calibration when the fore optics is fully filled by a uniform calibration source. However, the radiance FOV of the instrument must be determined during characterization.

Excluding sensors with a very small FOV (i.e., typically smaller than 1°), the determination of the FOV is performed with the instrument operated on a rotational stage with the entrance aperture of the radiometer aligned with the rotation axis. A stable light source with a small filament is placed in front of the instrument several meters away. The distance required depends on the FOV of the radiometer and the size of the filament, but must be sufficient to have the apparent size of the filament be a small fraction (tentatively 1/20) of the radiometer FOV. The on axis, *i.e.*, 0°, mechanical alignment can be performed using the window surface as the reference, by simply adjusting the rotation angle of the radiometer to get the reflection of the lamp filament to return on axis. Data should be ideally collected at increments approximately 1/20 of the estimated radiometer FOV over two planes with a positioning uncertainty better than 1/10 of the increment spacing. In the case of in-water characterizations, the in-air measurement angles θ_a are converted to the corresponding in-water angles $\theta_w(\lambda)$ using the relation (through the small angle approximation):

$$\theta_w(\lambda) = \frac{\theta_a}{n_w(\lambda)} \tag{20}$$

After normalization of the angular response function to the maximum value, the full-angle FOV, θ_{FOV}, is determined as the FWHM of intensity points.

Cosine Response

Irradiance sensors are equipped with collectors that should exhibit a cosine response as a function of the incidence angle θ. However, actual collectors always show angular response deviating from this ideal. This becomes a source of errors in measurements. Because of this, the directional response of cosine collectors must be characterized.

Due to the different refractive index of the medium in which the radiometers may be operated, the spectral directional response of E_s sensors need to be determined in air, while the in-water E_d and E_u sensors need to be measured immersed. Considering the large variability affecting the cosine response of instruments within a manufacturing series (Mueller 1995; Zibordi and Bulgarelli 2007;

Mekaoui and Zibordi 2013), the angular response of each radiometer should be characterized individually.

A measuring set-up for the characterization of an in-water sensor, requires the use of a tank. Following (Petzold and Austin 1988), the instrument is operated either in air or in a tank filled with water while supported by a fixture designed to allow rotation about an axis through the surface and center of the collector. A tungsten-halogen lamp with a small filament is enclosed in a housing with a small exit aperture and placed 1 m (or more) from a large optical window in the tank or from the collector. The collector is placed approximately 25 cm (or more) behind this window. A circular baffle should be placed immediately in front of the window to reduce stray light. When performing characterizations of immersed radiometers, the use of pure water minimizes scattering effects.

The $\theta = 0°$ alignment should locate the center of the collector on the axis of illumination with the collector surface oriented normal to the axis. One method of effecting this alignment is to pass a laser beam through the location of the filament to the center of the collector. The collector is rotated until a mirror held flat against it reflects the laser beam back on itself. The rotational indexing scale should be zeroed in this position. With $\theta = 90°$ the beam should just graze the collector, while it should remain in the center of the collector at any other smaller angle. The alignment and rotational apparatus should be adjusted until these angular alignment criteria are satisfied. Note that success in this alignment procedure also depends on orienting the illumination axis normal to the tank window.

With a lamp-to-collector distance of 1.25 m the fall-off at the outer edge of a 6 cm diameter collector is 0.9994, or -0.06 %, when the diffuser is at $\theta = 0°$. The net effect over the entire area of the diffuser is 0.9997 or -0.03 %. When $\theta = 90°$, with the diffuser edge-on to the lamp, the distance to the lamp varies for different points on the surface. The net error over the entire surface for this condition is 0.99997 or -0.003 %. All other angles fall between these limiting cases.

The instrument response $DN(0,\phi,\lambda)$ is initially recorded for $\theta = 0°$ in the plane determined by the azimuth angle ϕ. The instrument is rotated ideally with $1°$ increments up to to $\theta = 90°$, and the instrument responses $DN(\theta,\phi,\lambda)$ recorded at each angle θ. The $DN(0,\phi,\lambda)$ value is acquired at the beginning, the middle, and the end of each run and examined as a measure of lamp and instrument stability over the time involved. If the angular indexing mechanism allows rotation in either direction, the procedure should then be repeated for the azimuth $\phi+\pi$ to complete the characterization of the directional response in one full plane perpendicular to the collector surface. If the apparatus allows rotation in one direction only, then the instrument should be rotated about the optical axis (normal to the collector), and the procedure repeated to complete the plane. At least two sets of such runs should be made for different planes through the surface of the diffuser. The directional response of the instrument for each azimuth is expressed as

$$DN_N(\theta,\phi,\lambda) = \frac{DN(\theta,\phi,\lambda) - DN_{amb}(\theta,\phi,\lambda)}{DN(0,\phi,\lambda) - DN_{amb}(0,\phi,\lambda)}, \tag{21}$$

For an ideal cosine collector $DN_N(\theta,\phi,\lambda)$ should equal $\cos\theta$, regardless of ϕ and λ.

Note also that the ambient (occulted) signal, $DN_{amb}(\theta,\phi,\lambda)$, should be measured for each viewing geometry defined by (θ,ϕ).

For convenience, by fitting $DN_N(\theta,\phi,\lambda)$ as a function of θ to a third-order polynomial function (or even higher order, depending on the features shown by the experimental data), the fitted $DN_N(\theta,\phi,\lambda)$ can be applied to compute the cosine error for any angle θ

$$f_c(\theta,\phi,\lambda) = \frac{DN_N(\theta,\phi,\lambda)}{\cos\theta} - 1, \tag{22}$$

or, when considering the average response $\overline{DN}_N(\theta,\lambda)$ of $DN_N(\theta,\phi,\lambda)$ values over different azimuth angles,

$$f_c(\theta,\lambda) = \frac{\overline{DN}_N(\theta,\lambda)}{\cos\theta} - 1. \quad (23)$$

Applying $\overline{DN}_N(\theta,\lambda)$, the error $\varepsilon_c(\lambda)$ in measuring the irradiance for a uniform radiance distribution is computed from

$$\varepsilon_c(\lambda) = \frac{\int_\theta^{\pi/2} \overline{DN}_N(\theta,\lambda)\sin\theta d\theta}{\int_\theta^{\pi/2} \cos\theta \sin\theta d\theta} - 1. \quad (24)$$

Similarly, for a radiance distribution of the form $1+4\sin\theta$, which may be applied to approximate upward irradiance, the error is given by

$$\varepsilon_c(\lambda) = \frac{\int_\theta^{\pi/2} \overline{DN}_N(\theta,\lambda)(1+4\sin\theta)\sin\theta d\theta}{\int_\theta^{\pi/2} \cos\theta\,(1+4\sin\theta)\sin\theta d\theta} - 1. \quad (25)$$

The asymmetry of the cosine response can be estimated as the ratio of sums of values at opposite azimuth angles in the same plane, i.e., ϕ and $\phi+\pi$, according to

$$\delta_c(\phi,\lambda) = \frac{\int_0^{\pi/2} DN_N(\theta,\phi,\lambda)\sin\theta d\theta}{\int_0^{\pi/2} DN_N(\theta,\phi+\pi,\lambda)\sin\theta d\theta} - 1. \quad (26)$$

Any offset of the average asymmetry with the mechanical axis could be due to any one of the following causes: poor alignment; tilt of the diffuser; a non-centered detector array; or nonuniformity of the diffuser or of internal optical components. Variations in asymmetry from channel to channel of the same radiometer may be due to the placement of the individual detectors behind the diffuser.

The German Institute of Standardization defined the following performance index (see DIN5032, German Institute of Standardization, 1978) for irradiance collectors determined by the integral of azimuth-independent absolute values of the cosine error for θ in the 0 – 85° interval

$$\langle |f_c(\lambda)| \rangle = \int_0^{0.47\pi} |f_c(\theta,\lambda)| \sin(2\theta) d\theta. \quad (27)$$

The value of the index $\langle |f_c(\lambda)| \rangle$ is null for ideal cosine collectors, and increases with a decrease of the collector performance. Values in the range of 0.01 to 0.05 (i.e., 1 and 5 in percent) were computed for collectors in commercial radiometers (Mekaoui and Zibordi 2013).

By neglecting the sky light and thus only considering the direct sun component, an approximate impact of cosine errors $\varepsilon_c(\theta_0,\lambda)$ in $E_s(\lambda)$ is given by $\varepsilon_c(\theta_0,\lambda) \approx f_c(\theta_0,\lambda)$. However, validation activities require the delivery of highly accurate values of $E_s(\lambda)$. It is then important to apply corrections to measurements performed with non-ideal cosine collectors, once these are carefully characterized. Following the scheme applied by Zibordi and Bulgarelli (2007) and originally proposed for the ultraviolet spectral region by Seckmeyer and Bernhardt (1993), errors affecting actual measurements can be computed from

$$\varepsilon_c'(\theta_0,\lambda) = \langle f_c(\lambda) \rangle \frac{I_r(\theta_0,\lambda)}{I_r(\theta_0,\lambda)+1} + f_c(\theta_0,\lambda)\frac{1}{I_r(\theta_0,\lambda)+1} \quad (28)$$

where $I_r(\theta_0,\lambda)$ is the diffuse to direct irradiance ratio and

$$\langle f_c(\lambda) \rangle = \int_0^{\pi/2} f_c(\theta,\lambda)\sin(2\theta) d\theta. \quad (29)$$

Cosine errors affecting field data $\left[DN(\lambda) - DN_{dark}(\lambda)\right]$ are finally corrected by applying the factor

$$\aleph_c(\theta_0,\lambda) = 1 - \varepsilon_c^{'}(\theta_0,\lambda) \tag{30}$$

An analysis by Zibordi and Bulgarelli (2007) showed an agreement generally better than 2% between values of $\varepsilon_C^{'}(\theta_0,\lambda)$ computed with the above equation and equivalent values determined with radiative transfer simulations accounting for atmospheric optical properties and the actual characterization of the angular response of the collector. Nevertheless, differences are well below 0.5% for sun zenith angles lower than 65° and collectors exhibiting performance indices better than 2.5.

7 LINEARITY OF RESPONSE

The standard method to characterize the linearity of radiometers is conveniently performed using a point source and applying the inverse-square law. This solution generates different intensities by changing the distance between source and detector. Practically, it is recommended that characterizations rely on series of measurements ideally performed over the full dynamic range of each spectral band with fluxes incremented or decremented by 5 db (0.5 log).

It is mentioned that a variety of fluxes can be obtained with 1000 W tungsten-halogen projection lamps and additionally from 900 W to 2000 W high pressure xenon arc lamps. These latter lamps can produce irradiance levels approximating the full sunlight.

The straightforwardness of the characterization for sensor linearity, is however complicated by a number of elements. First, the inverse square law exactly applies to a point aperture and a point source. Thus, its inaccuracy increases with the size of the sensor aperture and the lamp filament, and additionally with a decrease of the distance between the two. This requires applying correction models accounting for the equivalent source and sensor aperture radii (Manninen *et al*. 2008). Further difficulties are created by the need to determine the actual reference planes for the lamp and of diffusers (see *Irradiance Responsivity Calibration*).

Defining $DN_r(\lambda)$ and $DN_0(\lambda)$ as the digital values corrected for ambient values corresponding to measurements performed at sensor-source distances r and r_0, respectively, with $DN_0(\lambda)$ reference value conveniently determined to approximately match half of the counts range, the non-linearity error is given by

$$\varepsilon_l\left[DN_r(\lambda)\right] = \frac{DN_r(\lambda)}{DN_0(\lambda)}\frac{(r+\Delta_f)^2}{(r_0+\Delta_f)^2} - 1 \tag{31}$$

It is mentioned that Eq. 31 neglects the effects of non-negligible size of sensor aperture and source and additionally, in the case of hyperspectral radiometers, assumes that $DN_r(\lambda)$ and $DN_0(\lambda)$ values are taken with the same integration time.

By imposing a linear dependence of non-linearity with digital counts, the non-linearity factor $l(\lambda)$ can be derived from the linear regression of $\varepsilon_l\left[DN_r(\lambda)\right]$ as a function $\left[DN_r(\lambda) - DN_0(\lambda)\right]$ so that

$$\varepsilon_l\left[DN_r(\lambda)\right] = l(\lambda)\cdot\left[DN_r(\lambda) - DN_0(\lambda)\right] \tag{32}$$

Once characterized, any departure from linearity must be incorporated into the calibration function and properly applied to field measurements. Practically, corrections of raw values $\left[DN(\lambda) - DN_{dark}(\lambda)\right]$ are obtained through the application of the factor

$$\aleph_l(DN,\lambda) = 1 - l(\lambda)\cdot\left\{\left[DN(\lambda) - DN_{dark}(\lambda)\right] - DN_0(\lambda)\right\} \tag{33}$$

It should be mentioned that there are other methods which rely on combinations of light sources, and allow the individual light sources to be uncalibrated (White et al. 2008: Hamadani et al. 2016). These methods maybe hard to physically implement, but may avoid the problem with non-ideal point sources and deviation from the ideal inverse square law.

8 INTEGRATION TIME RESPONSE

For instruments such as hyperspectral radiometers based on detector arrays, which allow operation with different integration times, the variation in response with integration time must be characterized. This is best done as a separate step after the sensor linearity is determined. Specifically, the integration time characterization is performed in a straightforward manner by looking at a constant source and measuring this source at different integration times. It is particularly important to characterize this at the short end of the integration times that will be used in either field or calibration, as this is the region where non-linear effects take place due to either mechanical shutter speed limitations, timing offsets, or any other factor related to charge handling from the elements of the detector array.

9 TEMPERATURE RESPONSE

The various components of a radiometer may be temperature dependent. For instance, silicon detectors commonly applied for ocean color applications, exhibit a significant temperature dependence in the near infrared spectral region. Because of this, in the absence of any temperature stabilization, the radiometer output may show changes in dark signal and responsivity. This requires that radiometers undergo a comprehensive temperature characterization at least for a few units of each class or series of instruments. Characterizations for underwater instruments should be performed over the 0 °C to 35 °C temperature range. In the case of E_S radiometers, the temperature range should embrace 0 - 45 °C . Sensors exhibiting temperature coefficients greater than 0.01 % per °C over these temperature ranges, should be more comprehensively characterized to establish the means and precision with which post-acquisition processing can be applied to correct for temperature dependence. Although knowledge of changes in the dark signal with temperature is essential for working at the lowest radiances or irradiances, it should be emphasized that more significant errors may be induced by temperature variations in responsivity.

Possible responsivity changes with temperature must be individually determined across the spectrum. Ideally, any correction should use the temperature of the affected element, which is normally in the interior of the instrument. This is best accomplished by routinely monitoring temperature sensors at critical locations within the instrument. For the highest precision, dynamic temperature testing involving temporal transients, as well as possible temperature gradients within an instrument, may be appropriate. In any case, at least one thermistor should be operated within the instrument near the detector.

Temperature characterizations require operating the radiometer in a temperature-controlled chamber while looking at a stable source. Following Zibordi *et al*. (2017), alignment of the different system components (i.e., source, optical window of the chamber, radiometer) should be performed with a laser. Stray light should be minimized using a diaphragm at the entrance window of the measuring chamber. Both the chamber and the internal instrument temperature should be measured to identify conditions of thermal equilibrium inside the instrument allowing measurements in stable conditions. This process should allow performing measurements when all the radiometer components have thermally stabilized. In the challenging condition created by the lack of any temperature measurement inside the instrument, extended time should be provided to the radiometer to stabilize. It is important to avoid direct illumination of the radiometer by the source between successive temperature tests (if operated at close distance) to avoid heating the foreoptics components. Measurements should be performed with increments of at least 5°C over the expected operating range of the instrument.

The response to temperature of radiometers can be defined through the relative difference $\varepsilon_T(T,\lambda)$ between values of $DN_T(T,\lambda) = \left[DN(T,\lambda) - DN_{amb}(T,\lambda)\right]$ determined at temperature T and values of

$DN_0(T_0,\lambda)=\left[DN(T_0,\lambda)-DN_{amb}(T_0,\lambda)\right]$ obtained at the reference temperature T_0 (typically set close to 20 °C, which corresponds to the temperature at which radiometers are commonly calibrated for responsivity)

$$\varepsilon_T(T,\lambda)=100\cdot\left[\frac{DN_T(T,\lambda)}{DN_0(T_0,\lambda)}-1\right] \tag{34}$$

where, assuming a linear dependence with temperature of the radiometer responsivity, the fitted values of $DN(T,\lambda)/DN(T_0,\lambda)$ are applied to determine the temperature coefficinet $c(\lambda)$ in units of $(°C)^{-1}$ as a function of $\Delta T=T-T_0$ for each band, so that

$$c_T(\lambda)=\left[\frac{DN(T,\lambda)}{DN(T_0,\lambda)}-1\right]\cdot\Delta T^{-1}. \tag{35}$$

The dependence to temperature response in field data $\left[DN(\lambda)-DN_{dark}(\lambda)\right]$ is finally removed by applying the factor

$$\aleph_c(\theta_0,\lambda)=1-c_T(\lambda)\cdot\Delta T \tag{36}$$

10 POLARIZATION SENSITIVITY

Light from the sea has a degree of polarization varying with water constituents and the atmospheric aerosols with impact more pronounced in above-water than in in-water radiometry. Because of this, the polarization sensitivity of radiometers due to individual optical components (e.g., optical windows, lenses, dispersive elements) may become the source of uncertainty in measurements. Thus at a minimum, the polarization sensitivity of optical radiometers must be determined. Considering that the circular polarization of radiance in the atmosphere and natural waters is generally negligible, the characterization for polarization sensitivity reduces to linear polarization analysis. This can be achieved by incrementally rotating a linear polarizer positioned between a non-polarized source and the entrance optics of the radiometer. The resulting polarization sensitivity, in percent, can then be expressed as

$$P(\lambda)=100\cdot\frac{DN_M(\lambda)-DN_m(\lambda)}{DN_M(\lambda)+DN_m(\lambda)} \tag{37}$$

where $DN_m(\lambda)$ and $DN_M(\lambda)$ indicate the minimum and maximum values recorded while rotating the polarizer and corrected for the ambient signal.

In the case of sensitivity to linear polarization tentatively higher than 1%, corrections should be definitively applied for comprehensively characterized radiometers (Meister *et al.* 2005, Talone and Zibordi 2018). Still, best practice would suggest reducing polarization sensitivity through depolarizers placed inside the radiometer optics.

11 SENSITIVITY CHANGE

Responsivity of radiometers may change over time because of aging of optical components (e.g., filters, fore optics). Tracking of these changes is essential and imposes pre- and post-field absolute radiometric calibrations and, ideally, regular responsivity checks through portable reference sources during field activities. Responsivity changes of a very few percent (e.g., 2% or even larger when supported by regular checks) generally can be corrected assuming linear variations with time. Conversely, caution is suggested while correcting responsivity changes reaching several percent. In fact, these could result from abrupt variations in the characteristics of optical components such as those subsequent to a deterioration of interference filters due to humidity effects or thermal stress of gratings.

12 TEMPORAL RESPONSE

The temporal response of a spectrometer may be examined by introducing a step function of near full-scale flux to the system using an electrically operated shutter and measuring the system transient response at 0.1 s, or shorter (depending on acquisition rate), intervals. The response should be stable within one digital count, or 0.1 %, whichever is greater, of the steady state value in one second or less.

13 PRESSURE EFFECTS

Pressure can cause radiometric measurement errors by deforming irradiance collectors. Pressure coefficients associated with polytetrafluoroethylene (PTFE) based irradiance diffusers are known to exist, but they are not uniform and there may be hysteresis effects. It is recommended that each type of irradiance detector be examined for variations in responsivity with pressure. If a significant effect is observed, then pressure-dependent responsivity coefficients should be determined separately for each instrument and collector. The pressure characterization should also test for, and quantify, hysteresis and temporal transients in responsivity under a time varying pressure load. The characterization of pressure effects is not common practice, and the requisite procedures are not defined.

14 SUMMARY OF TARGET UNCERTAINTIES

This final session aims at summarizing the expected instrumental uncertainty values. Specifically, table 2 lists the "best effort" uncertainties achievable with current technology and expertise, which affect the basic radiometric quantities from in- and above-water radiometry.

Table 3 summarized some requirements for spectral bands and for radiometer attitude during field operations.

Table 2. Target uncertainties for most relevant radiometric quantities.

	L_u	L_i	L_T	E_d	E_u	E_s
Responsivity [%]	2	2	2	1.5	1.5	1.5
Out of Band Response [%]	1	1	1	1	1	1
Stray Light [%]	1[1]	1[1]	1[1]	1[1]	1[1]	1[1]
Immersion Factor [%]	0.2			0.5	0.5	
Cosine Response [%]				3	3	0.5[1,2]
Linearity [%]	0.1[1]	0.1[1]	0.1[1]	0.1[1]	0.1[1]	0.1[1]
Polarization Sensitivity [%]	1	1	1	0.2	0.2	0.2
Sensitivity change [%]	0.2[1]	0.2[1]	0.2[1]	0.2[1]	0.2[1]	0.2[1]

[1] Corrected in the relevant range of variation
[2] With sun zenith angle in the range of 0-65°

Table 3. Requirements for spectral bands and radiometers attitude.

	L_u	L_i	L_T	E_d	E_u	E_s
Center wavelength [nm]	1	1	1	1	1	1
Band width [nm]	1	1	1	1	1	1
Attitude [deg^{-1}]	5	5	2	2	2	1

15 FUTURE DIRECTIONS

In addition to continuously improving protocols for a comprehensive characterization of radiometers and a throughout implementation of correction schemes reducing uncertainties in field data, it would be relevant to construct libraries of characterization parameters determined across different laboratories for commercial radiometers widely used by the scientific community.

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Chapter 4: In-Water Radiometry Measurements and Data Analysis

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1. INTRODUCTION

In water radiometric profiling is a reliable methodology to measure the spectral upwelling radiance $L_{\mathrm{u}}(z,\lambda)$, downward irradiance $E_{\mathrm{d}}(z,\lambda)$ and additionally the upwelling irradiance $E_{\mathrm{u}}(z,\lambda)$ at various depths z. These measurements are commonly performed with profiling systems such as free-falls or floats in conjunction with the collection of above-water downward spectral irradiance data $E_{\mathrm{S}}(\lambda)$. Primary data products from profile measurements, in the context of satellite validation, are the values extrapolated to the sub-surface depth $z = 0^{-}$ of $L_{\mathrm{u}}(0^{-},\lambda)$, $E_{\mathrm{d}}(0^{-},\lambda)$ and $E_{\mathrm{u}}(0^{-},\lambda)$. Reliable extrapolations require measurements collected in the first optical depth and the capability of producing a number of measurements per unit depth to allow the minimization of the perturbing effects due to wave focusing and defocusing. It is essential that radiometric data supporting satellite ocean color validation activities are performed during clear sky conditions (at least with clear sun and low cloud coverage) in regions allowing negligible bottom perturbations and far enough from land to assume negligible adjacency effects in satellite matchup analysis.

The following sections mostly focus on free-fall optical profiling. Still, when relevant, mention is made to alternative in-water methods relying on profiling floats and buoy systems, which share common deployment and data processing elements with free-fall optical profiling.

2. MEASUREMENTS

In-water radiometric profiling largely rely on deployment systems such as free-falls operated up to several tens of meters from deployment platforms (Waters *et al.* 1990, Hooker and Maritorena 2000). These measurement systems, which allow sampling from near the surface up to several tens of meters depth and the minimization of the impact of deployment platforms (Gordon 1985, Voss *et al.* 1986), have replaced the previous winched systems requiring extended analysis to quantify superstructure perturbations affecting radiometry data.

Besides avoidance of superstructure perturbations, a number of additional deployment requirements must be met to minimize uncertainties in measurements. These imply: i. using radiometers and deployment devices (e.g., free-falls) minimizing the so-called self-shading resulting from the perturbation of the light field by the measurement system itself (Gordon and Ding 1992); ii. producing a statistically significant number of measurements from near the sea surface up to a few meters depth ideally benefitting from vertically homogeneous optical properties of the water; iii. determining the pitch and roll of each measuring component (e.g., free fall and above water reference unit); iv. recording system offsets (i.e., dark signals for optical sensors and pressure tare for depth sensors) in view of allowing the removal of potential unwanted biases in recorded data.

Avoidance of perturbations by deployment structures

The complete avoidance of perturbations by deployment structures is a mandatory requirement for all radiometric measurements and, as already stated, free falls offer the capability of deploying the measurement system far away from the deployment structure. To a first approximation, the minimum safe deployment distance will vary with the optical properties of the water. By considering deployments performed from the stern of a ship with the sun off of the bow and considering that the various quantities measured (i.e., $E_d(z,\lambda)$, $E_u(z,\lambda)$, and $L_u(z,\lambda)$) are affected differently by the deployment structure as a function of distance, a practical approach would suggest profiling at a distance that ensures negligible effects to any quantity in any spectral band. Following Mueller (2002), the sampling distance d from large deployment structures should be $d > 3/K_m$, with K_m indicating the minimum spectral value for the subsurface values of K_L, or K_d, or K_u. Such a conservative approach, however, may provide largely overestimated distances in oligotrophic waters.

In the case of $E_s(\lambda)$ measurements, superstructure perturbations can only be avoided by deploying the radiometer above any obstacle that may be seen by the 2π field-of-view (FOV) of the radiometer. Such a fundamental requirement is often challenged by the difficulty to reach the highest locations of deployments structures (e.g., ships) or the operational need to ensure daily maintenance to radiometers. A practical solution is often offered by the use of telescoping poles.

Specific systems such as profiling floats, may not have E_s sensors (Gerbi *et al.* 2016). In such a case $E_s(\lambda)$ can be determined from $E_d(0^-,\lambda)$ (e.g., $E_S(\lambda)$=0.96 $E_d(0^-,\lambda)$). It must be recognized, however, that such a determination of $E_S(\lambda)$ is affected by focusing and defocusing effects (Zibordi *et al.* 2004). Because of this, and in view of minimizing uncertainties, it is emphasized that $E_S(\lambda)$ should be derived from in-water determinations of $E_d(0^-,\lambda)$ only if $E_s(\lambda)$ cannot be directly measured. Another alternative, applicable in the absence of both $E_S(\lambda)$ and $E_d(0^-,\lambda)$ values, is provided by the theoretical determination of $E_S(\lambda)$. Such a solution implemented through the computation of the diffuse atmospheric transmittance (Tanre *et al.* 1979), has shown satisfactory results during clear sky conditions (Zibordi 2012) but with larger uncertainties and requiring knowledge of the aerosol optical depth .

Finally, the operation of radiometers should be restricted to specific locations of the profiling system that minimize measurement perturbation: the E_d sensor must be located in the uppermost part of the system and the E_u sensor in the lowermost one. Additionally, in the case of long profilers, the use of a large full-angle FOV for L_u measurements (still not exceeding 20°) implies operating the sensor at a distance from the main system components to provide a clear FOV for the sensor.

Self-shading minimization

Self-shading implicitly effects of $E_u(z,\lambda)$ and $L_u(z,\lambda)$ data (Gordon and Ding 1982). This perturbation largely varies with the size of the radiometer and system design, the water optical properties, and the illumination conditions. Thus, aside from using radiometers and profiling devices with small dimensions, it is essential that i. L_u radiometers are always operated on the side of the system directly illuminated by the sun; and additionally, ii. E_u radiometers are operated from the lowermost location of the profiling device so that no single component of the measuring system falls in the field of view.

Bio-fouling avoidance

Bio-fouling generally affects any optical component operated in water for extended periods. Thus, bio-fouling is not an issue for manned free-falling systems, but is for any system such as autonomous floats or buoy systems. Mitigation of the problem, typically a result of the growth of bacteria and algae, can be obtained with plates or rings of copper installed nearby the radiometer fore optics. In the case of floats, the problem is minimized by positioning the system very deep when not in operation.

Depth resolution

Waves introduce focusing and defocusing perturbations in profile data (Zaneveld *et al.* 2001). These effects largely vary with the size of the detector (Darecki 2011), the optical properties of water, the deployment speed, the illumination conditions, and, when applicable, the integration time. A limited number of data in the extrapolation depth may thus become the source of large uncertainties in computed subsurface values. Consequently, it is essential that the density of measurements (i.e., the number of data per unit depth) comprehensively represents the light field variability at each measurement depth (Zibordi *et al.* 2004, D'Alimonte *et al.* 2010). A statistically representative number of data per unit depth requires a low deployment speed or a high acquisition rate, or better, a combination of the two (still, considering that light variability is better captured when decreasing the deployment speed rather than increasing the acquisition rate). While some profilers can meet requirements on depth resolution (Hooker et al. 2013), others may exhibit limits both in deployment speed (that may not be reduced below a certain limit to ensure an acceptable system attitude while profiling) or in acquisition rate. In such a case, a practical solution is offered by the combination of successive independent profiles into a single one or, alternatively, the collection of a single composite profile comprising data from successive concatenated casts (Zaneveld *et al.* 2001, Zibordi *et al.* 2004, Voss *et al.* 2010) . This technique, so-called multicasting, was shown effective in lessening wave perturbations in regression products from both multispectral and hyperspectral systems (D'Alimonte *et al.* 2018). Specific investigations indicated that the density of measurements reducing the uncertainty below a given threshold significantly changes for the various sensors (i.e., L_u, E_d and E_u) as function of sea state, optical properties of water and wavelength. Choosing a 2% uncertainty target for the subsurface values computable from profile data, and combining results from different studies focused on both multispectral and hyperspectral sensors (Zibordi *et al.* 2004, D'Alimonte *et al.* 2018), tentatively at least 10, 50 and 20 measurements per meter are required for $L_u(z,\lambda)$, $E_d(z,\lambda)$ and $E_u(z,\lambda)$. These measurements per meter, in combination with the sampling rate for multispectral systems or the integration time for hyperspectral systems, determine the minimum number of independent profiles or concatenated casts necessary to satisfy depth resolution requirements.

Offset recording

The offsets of depth sensors and of radiometers, i.e., the signals measured with the profiling system out of the water and the optical sensors capped, generally exhibit temperature dependence. These offsets can easily change with time as a function of the environmental conditions. It is thus essential that each sequence of optical measurements is accompanied by an offset determination. Also, when there is a large difference between the air and water temperatures, the in-water radiometers should be allowed to equilibrate with water temperature at the beginning of the measurement station. Ideally, thermistors inside radiometers would provide access to temperature values allowing corrections for non-negligible offsets.

Besides radiometers, depth sensors also exhibit offset changes with temperature and atmospheric pressure. Thus since the accuracy of depth is essential for the determination of accurate sub-surface values, the depth offset should always be recorded for each deployment or sequence of deployments.

Measurement sequence

Each measurement sequence should provide contemporaneous measurements of $E_s(\lambda)$, $L_u(z,\lambda)$, $E_d(z,\lambda)$ and $E_u(z,\lambda)$. Best practice suggests that each determination of sub-surface values should rely on profiles (i.e., single or multiple in the case of multi-casting) collected during a measurement sequence lasting a very few minutes. Multiple measurement sequences are essential to support the quality assurance of data and additionally to quantify the environmental perturbations affecting of $L_u(0^-,\lambda)$, $E_d(0^-,\lambda)$ and $E_u(0^-,\lambda)$. Finally, as already anticipated, each measurement sequence, or multiple sequences, should include specific offset measurements.

Essential ancillary data

A number of ancillary data are required for the processing of and to quality check in-water radiometric data. These comprise: date and time (UTC); longitude and latitude; bottom depth; cloud cover (likely documented through digital pictures or videos), and sea state; wind speed and direction, air and water temperature; barometric pressure; water salinity. Additional quantities likely required for the correction of the self-shading perturbations (see next section) are the total spectral absorption coefficient of water $a(\lambda)$ and the spectral diffuse to direct irradiance ratio $I_r(\lambda)$. This latter could be experimentally determined from $E_s(\lambda)$ measurements by alternatively measuring the downward irradiance with the direct sun irradiance occulted (diffuse) and the unocculted E_s signal (diffuse +direct).

The attitude of sensors with respect to the vertical is a critical factor for $E_s(\lambda)$, $E_d(z,\lambda)$, $E_u(z,\lambda)$ measurements and slightly less for $L_u(z,\lambda)$. Thus, in view of allowing the removal of data affected by excessive tilts, it is essential that roll and pitch are measured and recorded concurrently with radiometric values for both in-water and in-air systems.

3. DATA ANALYSIS

Data products from profile data are the subsurface radiometric values of $L_u(0^-,\lambda)$, $E_d(0^-,\lambda)$ and $E_u(0^-,\lambda)$, and their respective attenuation coefficients $K_L(\lambda)$, $K_d(\lambda)$ and $K_u(\lambda)$, determined in a near surface extrapolation layer.

Accuracy of derived data products, in addition to the accuracy of calibration and characterization factors applied to radiometry and depth data, largely depends on: i. the minimization of the impact of outliers or in general of any measurement artifact (e.g., elevated tilt); ii. the extrapolation layer selected; iii. the extrapolation method; iv. the accuracy of the correction applied for self-shading perturbations.

The key radiometric quantities are the subsurface (0^-) values that cannot be directly measured due to wave perturbations. This section introduces the methods required to process profile measurements of $E_\mathrm{d}(z,\lambda)$, $E_\mathrm{u}(z,\lambda)$, and $L_\mathrm{u}(z,\lambda)$ in view of deriving the subsurface quantities.

Offset removal, corrections for the non-ideal performance of sensors and calibration

The instrument dark signal in each channel, ideally recorded for each profile or sequence of profiles, must be subtracted from the raw data prior to any further processing. This also applies for the depth sensor data by accounting for the relative distance offsets between the depth sensor transducer and the aperture of the L_u, E_d and E_u radiometers. All corrections must be applied to minimize the non-ideal performance of the radiometer (e.g., temperature dependence, linearity, …) in conjunction with the application of immersion factors and the absolute calibration coefficients. These latter should result from pre- and post-field calibrations, and eventually the supplementary use of relative field calibrations performed with portable sources to monitor the stability of the sensors responsivity with time.

These early data reduction steps require consistent and comprehensive access to any information required for the processing and successive re-processing of field measurements. Best practice suggests an efficient data management system ensuring unique association of field data (i.e., profile and offset) to measurement campaigns, stations, casts, essential ancillary data and, obviously, radiometer tags and their calibration coefficients and correction factors.

Quality control of data

Quality checks should be applied to profile data prior to processing to ensure the highest accuracy to the derived products. First, in water profile data and $E_\mathrm{s}(\lambda)$ measurements affected by excessive roll or pitch should be removed through the application of tilt thresholds. These thresholds need to be chosen by trading off the number of measurements and the need for accuracy, appreciating that thresholds may vary from case to case as a function of the sea state and of the deployment platform (e.g., the size of the ship). Still, a threshold of 5°should be an upper limit for the in-water data, while it should ideally not exceed 2°for E_s measurements.

Additional quality checks should remove those measurement sequences affected by significant variability of $E_\mathrm{s}(\lambda)$ not explained by tilt perturbations. In particular, understanding the requirement of clear sun and low cloudiness, quality checks applied to $E_\mathrm{s}(\lambda)$ values (likely supported by analysis of digital pictures collected during field measurements) should aim at identifying those measurement sequences likely contaminated by clouds. These checks should rely on very small thresholds, ideally a very few percent change of the measured signal.

Finally, quality checks should apply to differences between the pre- and post-field calibrations of optical sensors. This step may benefit from field checks performed with portable reference sources. Thresholds in calibration differences should obviously account for the deployment duration and the working conditions. When considering well-maintained systems (e.g., regularly cleaned) and operated for a short time (e.g., up to a few weeks), differences between pre- and post-field calibrations should be mostly explained by calibration uncertainties. Slightly larger differences due to actual sensitivity decay with time, may require actions such as interpolations between calibrations. A large difference, which may challenge the determination of accurate radiometric products, should lead to the rejection of profile data, unless the cause can be isolated to some unique event and a timeline for applying pre- or post-calibrations determined.

Finally, surface effects can heavily impact measurements near the surface. As such, sufficient measurements are required in the very near surface to perform regressions, or conversely in the case of fixed-depth measurements for averaging over a time scale longer than that of surface fluctuations. The number of measurements should then reflect that already indicated in the previous section. A measurement density not fulfilling requirements in the extrapolation layer should lead to the rejection of the entire profile data.

Normalization by Surface Irradiance

Restating the fundamental requirement of performing radiometric measurements during ideal illumination conditions (i.e., clear sun and low cloudiness), changes in the illumination condition during measurements simply due to sun zenith changes may affect the accuracy of derived data products. By introducing the time dependence t, these changes are minimized through $E_s(\lambda,t)$ measured over the duration of a radiometric cast simultaneously with $L_u(z,\lambda,t)$, $E_u(z,\lambda,t)$ and $E_d(z,\lambda,t)$. Recalling that in-water radiometric data and $E_s(\lambda,t)$ measurements are subject to independent filtering for tilt perturbations, the available $E_s(\lambda)$ measurements need to be applied for extrapolating missing values at times t matching the in water data.

An essential step in data reduction is to account for the effects of changes in the incident light field during data collection. Using $\Im(z, \lambda, t)$ to represent the various radiometric quantities (i.e., $L_u(z,\lambda,t)$, $E_u(z,\lambda,t)$ and $E_d(z,\lambda,t)$), and assuming that the transmission of $E_s(\lambda,t)$ through the surface does not vary with time, changes due to the incident light are accounted through

$$\Im_0(z,\lambda,t_0) = \frac{\Im(z,\lambda,t)}{E_s(\lambda,t)} E_s(\lambda,t_0) \tag{1}$$

where $\Im_0(z, \lambda, t_0)$ is the radiometric quantity normalized to the incident light field at t_0, $E_s(\lambda, t_0)$, with t_0 generally chosen to coincide with the beginning of the acquisition sequence (but, a different reference time can be safely chosen).

It is important that the spectral bands of the E_s sensor closely match those of the in-water sensors to avoid introducing spectral artifacts in the normalized data. In fact, any appreciable spectral mismatch of inter-sensor bands would lead to an increase of uncertainties in the normalized and, in general, any derived radiometric quantity.

Extrapolation of Sub-Surface Values

The first step in the determination of sub-surface radiometric values from profile measurements is the determination of the extrapolation interval. Best practice suggests that regressions are performed using measurements in the top optical depth (i.e, between the surface and $1/K_d(\lambda)$). Still, inhomogeneity of the extrapolation layer together with focusing and defocusing effects may challenge its determination. The process leading to the determination of the extrapolation interval should benefit from the visualization of profile data at various spectral bands in view of choosing the upper (typically within a few tens of centimeters from the surface) and lower (at least a few meters below the surface) boundaries. Trial linear regressions of log-transformed data as a function of depth, may provide evidence of the actual exponential decay of data in the extrapolation interval selected. Successive trials and the analysis of the standard deviation of differences between fitted and binned data at discrete depth intervals may support the selection of the most appropriate extrapolation interval. This processing step should also include filtering of outliers that may affect the very near surface data. A convenient way is to apply a data exclusion threshold based on the standard deviation of the difference between fitted and actual data. For instance, individual data should be removed when the difference between the fitted and actual value exceeds 3 standard deviations.

The selection of the extrapolation layer can be independently performed for each spectral band. This choice, which allows limiting the impact of inelastic scattering which restricts the depth of the extrapolation layer in the red bands, should be only applied to cases exhibiting high vertical homogeneity of the optically active components across the maximum extrapolation interval. Conversely, in the presence of vertical inhomogeneity often occurring in coastal optically complex waters, a single extrapolation layer for all the bands is preferable in view of producing radiometric products for the same water layer and consequently for the same distribution of water constituents.

Omitting the dependence with time and assuming that measurements satisfy the requirement of linear decay of ln $\Im_0(z, \lambda)$ with depth in the extrapolation interval identified by $z_0 < z < z_1$, the sub-surface values $\Im_0(0^-, \lambda)$ (i.e., $L_u(0^-, \lambda)$, $E_d(0^-, \lambda)$ and $E_u(0^-, \lambda)$) are determined as the exponential of the intercepts from the least squares linear regressions of $ln\ \Im_0(z, \lambda)$ versus z. The negative values of the slopes of the regression fits are the so-called diffuse attenuation coefficients $K_\Im(\lambda)$ (i.e. $K_L(\lambda)$, $K_d(\lambda)$, and $K_u(\lambda)$) for the selected extrapolation interval. Thus, the determination of the subsurface values is addressed as a linear problem relying on the logarithmic transformation of radiometric data as a function of depth. Specifically, by assuming an exponential decay of $\Im_0(z,\lambda)$ and a constant value of $K_\Im(\lambda)$ in the extrapolation layer

$$\Im_0(z,\lambda) = \Im_0(0^-,\lambda) \cdot e^{-K_\Im(\lambda)\cdot z} \tag{2}$$

in logarithmic scale given by

$$\ln\left[\Im_0\left(z,\lambda\right)\right]=\ln\left[\Im_0\left(0^-,\lambda\right)\right]-K_\Im(\lambda)\cdot z, \tag{3}$$

the determination of $\Im_0\left(0^-,\lambda\right)$ and $K_\Im(\lambda)$ is obtained from the minimization of the sum-of-square errors SSE_L

$$SSE_L\left[\Im_0\left(0^-,\lambda\right),K_\Im(\lambda)\right]=\sum_{i=1}^{N}\left\{\ln\left[\Im_0\left(z,\lambda\right)\right]-\ln\left[\Im_0\left(0^-,\lambda\right)-K_\Im(\lambda)\cdot z\right]\right\}^2 \tag{4}$$

It is emphasized that the linearity of the log-transformed radiometric profiles with depth is an approximation because of changes in the radiance distribution in the near surface due to scattering, absorption, wave perturbations, and, additionally, due to inelastic scattering processes such as Raman scattering (Sugihara et al. 1984: Stavn and Weidemann 1988: Gordon 1999) and chlorophyll-*a* fluorescence (Gordon 1979) at some wavelengths. To account for the wave perturbation effect on $E_d(0^-, \lambda)$ and to a lesser extent $L_u(0^-, \lambda)$ and $E_u(0^-, \lambda)$, an alternative approach for the determination of $\Im_0\left(0^-,\lambda\right)$ and $K_\Im(\lambda)$ is offered by the minimization of the sum-of-square errors SSE_E without taking the logarithm of the $\Im_0\left(z,\lambda\right)$ values. i.e.,

$$SSE_E\left[\Im_0\left(0^-,\lambda\right),K_\Im(\lambda)\right]=\sum_{i=1}^{N}\left\{\Im_0\left(z,\lambda\right)-\Im_0\left(0^-,\lambda\right)e^{-K_\Im(\lambda)\cdot z}\right\}^2 \tag{5}$$

where minimization techniques such as the Trust-Region algorithm can be applied (D'Alimonte *et al.* 2013).

Investigations focussing on the comparison of the two regression approaches (D'Alimonte *et al.* 2013) indicated differences of the order of 1-2% for $L_u(0^-, \lambda)$ and values well exceeding 5% for $E_d(0^-, \lambda)$.

It is emphasized that extrapolating $E_\mathrm{d}\left(z,\lambda\right)$, $E_\mathrm{u}\left(z,\lambda\right)$, and $L_\mathrm{u}\left(z,\lambda\right)$ to $z=0^-$ becomes very difficult at $\lambda \geq 600$ nm for either method. At these wavelengths, the rapid decrease in daylight over an extremely shallow first attenuation length may compete with an increase in flux with depth due to inelastic scattering.

With reference to the depth *z* assigned to each radiometric measurement, it is important to underline the need to assign the exact depth value. Assuming accurate depth measurements and exact knowledge of the offsets between depth sensor and radiometers, it is important to assign the exact depth value to data collected at a constant rate with multispectral profilers. Conversely, it may require care when data are collected at a variable rate typical of hyperspectral systems which often exhibit a diverse collection frequency for each sensor as a result of using different integration times, some of which may reach several seconds. In such a case, best practice would suggest that the depth assigned to each radiometric value is determined accounting for: *i*. the depths corresponding to the start, and end, of each radiometric measurement performed with given integration time; and *ii*. a weight based on the diffuse attenuation coefficient (D'Alimonte *et al.* 2018).

Specifically, assuming an exponential decay of the radiometric profile data with depth, the value of the depth *z* associated to each radiometric measurement $\Im(z,\lambda,t)$ can be determined as

$$z=\frac{1}{-K_\Im^*(\lambda)}\left[\ln\left(e^{-K_\Im^*(\lambda)\cdot z_s^*}-e^{-K_\Im^*(\lambda)\cdot z_e^*}\right)-\ln\left(-K_\Im^*(\lambda)\cdot(z_s^*-z_e^*)\right)\right], \tag{6}$$

where $K_\Im^*(\lambda)$ is the attenuation coefficient determined from profile data using an extrapolation interval embracing the depths z_s^* and z_e^*.

To conclude, in addition to $L_u(0^-, \lambda)$, $E_d(0^-, \lambda)$ $E_u(0^-, \lambda)$ and the related $K_L(\lambda)$, $K_d(\lambda)$, and $K_u(\lambda)$ coefficients, other derived quantities of interest for remote sensing applications are the dimensionless irradiance reflectance at depth 0^-, $R(0^-, \lambda)$ defined as $E_u(0^-, \lambda) / E_d(0^-, \lambda)$, and the *Q*-factor at nadir, $Q_n(0^-, \lambda)$ in units of sr defined as $E_u(0^-, \lambda) / L_u(0^-, \lambda)$. An additional quantity, fundamental for ocean color studies, is the water–leaving radiance $L_w(\lambda)$ in units of W m^{-2} nm^{-1} sr^{-1} given by

$$L_w(\lambda)=L_u(0^-,\lambda)\frac{1-\rho(\lambda)}{n_w^2(\lambda)}, \tag{7}$$

where $n_w(\lambda)$ is the spectral refractive index of water and $\rho(\lambda)$ the reflectance factor of the sea surface. By neglecting the spectral dependence, the term $\left[1-\rho(\lambda)\right]/n_w(\lambda)$ is often assumed constant and set to 0.543 (Austin 1974). Recent investigations, however, showed that this approximation can introduce spectral uncertainties reaching 1% (Voss and Flora 2017).

Quality assurance of data

The quality assurance of data products can rely on a number of quality checks. First, the $K_{\Im}(\lambda)$ values must exhibit positive values, close or exceeding those of pure water. Negative values indicate regression problems likely due to the lack of measurements in the extrapolation layer, high perturbations due to wave focussing and defocussing, or inelastic scattering effects. Additional tests should involve, when both are available, spectral comparisons of $E_s(\lambda)$ and $E_d(0^-,\lambda)$. Significant differences exceeding the expected 4% between the two quantities, may indicate large wave perturbations, or an inappropriate selection of the extrapolation interval, both leading to a poor determination of $E_d(0^-,\lambda)$ data. Large differences between $E_s(\lambda)$ and $E_d(0^-,\lambda)$ may also indicate problems with the attitude of sensors, issues with the sensors calibration or characterization (e.g., cosine and temperature responses), which may lead to differences as a function of the operational conditions (e.g., sun zenith angle and, air and water temperature). Finally, when $E_u(0^-,\lambda)$ data are available, unrealistic spectral shape values of $Q_n(0^-,\lambda)$ would again suggest calibration and characterization issues with sensors or alternatively extrapolation problems.

Corrections for Instrument Self-Shading

The finite size of underwater radiometers affects the radiance field and induces errors in the measured upwelling radiance and upward irradiance (Gordon and Ding 2002). The problem is further increased by the geometrical complexity of profiling systems composed of radiometers and a number of components of non-negligible size (i.e., hubs, brackets, cables). An accurate determination of the shading effects in radiometric measurements performed with profilers requires investigations accounting for the geometric specificity of the various system components (Piskozub et al 2001, Leathers *et al.* 2001, Leathers *et al.* 2004, Shang *et al.* 2017). Still, without minimizing the importance of determining system shading perturbations in radiometric measurements, a first level of self-shading correction is often possible for cylindrically symmetric systems by simply accounting for the diameter of radiometers, the optical properties of water and illumination conditions. With reference to this specific correction, Gordon and Ding (1982) evaluated the self-shading error affecting subsurface upwelling radiance and upward irradiance for an ideal circular sensor of infinitesimal thickness. Through numerical simulations, they estimated errors ranging from a few percent up to several ten's percent. For a given radiometer, the self-shading error is much larger in the near infrared than in the visible because of the stronger water absorption, and it increases with the concentration of absorbing particles and the absorption coefficient of colored dissolved organic matter.

For practical purposes, the self-shading error $\varepsilon_{\Im}(\lambda)$ for the upwelling radiance or upward irradiance can be defined as

$$\varepsilon_{\Im}(\lambda) = \frac{\Im(0^-,\lambda) - \hat{\Im}(0^-,\lambda)}{\Im(0^-,\lambda)} \tag{8}$$

where $\Im(0^-,\lambda)$ indicates the radiometric quantity that would apply in the absence of the instrument, and $\hat{\Im}(0^-,\lambda)$ indicates the experimental quantity determined from field measurements. Gordon and Ding (1992) showed that the error $\varepsilon_{\Im}(\lambda)$ can be expressed as a function of the radius R_d of the radiometer, the absorption coefficient of the medium $a(\lambda)$, the sun zenith θ_0 and the ratio of diffuse to direct sun irradiance $I_r(\lambda)$ according to the following parameterization

$$\varepsilon_{\Im}(\lambda) = \frac{\varepsilon_{sun}(\lambda) + \varepsilon_{sky}(\lambda) \cdot I_r(\lambda)}{1 + I_r(\lambda)} \tag{9}$$

with

$$\varepsilon_{sun}(\lambda) = 1 - \exp[-k_{sun}(\lambda) \cdot a(\lambda) \cdot R_d] \tag{10}$$

and

$$\varepsilon_{sky}(\lambda) = 1 - \exp[-k_{sky}(\lambda) \cdot a(\lambda) \cdot R_d] \tag{11}$$

where $\varepsilon_{sun}(\lambda)$ and $\varepsilon_{sky}(\lambda)$ indicate the errors due to the direct sun irradiance and to diffuse radiance contributions, respectively.

Mueller and Austin (1995) proposed convenient parameterizations for the determination of $\varepsilon_{sun}(\lambda)$ and $\varepsilon_{sky}(\lambda)$ by accounting for the sensor-to-instrument radius f_R. In particular, for $k_{sun}(\lambda)$ they suggested

$$k_{sun}(\lambda) = (1 - f_R) \cdot k_{sun}^p(\lambda) + f_R \cdot k_{sun}^e(\lambda) \tag{12}$$

where $k_{sun}^p(\lambda)$ and $k_{sun}^e(\lambda)$ are terms representing the two extremes of a point sensor or a sensor having the same size as the instrument case, respectively.

Functions for the computation of $k_{sun}^p(\lambda)$, $k_{sun}^e(\lambda)$ and $k_{sky}(\lambda)$, accounting for the additional parameterizations proposed by Zibordi and Ferrari (1995) and formulated using the data published by Gordon and Ding (1982) for $a \cdot R_d < 0.1$ and sun zenith angles $30° < \theta_0 < 70°$, are summarized in Table 1.
Actual corrections for self-shading perturbations affecting $\Im(0^-, \lambda)$ are given by

$$\aleph_s(\lambda) = 1 - \varepsilon_{\Im}(\lambda) \tag{13}$$

Table 1: Functions for the computation of the terms: $k_{sun}^p(\lambda)$, $k_{sun}^e(\lambda)$ and $k_{sky}(\lambda)$. The symbol $\theta_{0w}(\lambda)$ indicates the sun zenith angle in the water (i.e., $\theta_{0w}(\lambda) = \sin^{-1}[\sin\theta_0 / n_w(\lambda)]$).

	L_u	E_u
$k_{sun}^p(\lambda)$	$(2.07 + 00056 \cdot \theta_0) / tg(\theta_{0w})$	$3.41 - 0.0155 \cdot \theta_0$
$k_{sun}^e(\lambda)$	$(1.59 + 00063 \cdot \theta_0) / tg(\theta_{0w})$	$2.76 - 0.0121 \cdot \theta_0$
$k_{sky}(\lambda)$	$4.61 - 0.87 \cdot f_R$	$2.70 - 0.48 \cdot f_R$

For computational purposes, the radius of an irradiance sensor approximately corresponds to the radius of the cosine collector. In the case of a radiance sensor it can be determined as $2h \cdot tg(\theta_{FOV} / 2)$ where h is the distance between the detector and the front plate of the radiometer, and θ_{FOV} is the full-angle FOV.

In the absence of actual determinations of water absorption $a(\lambda)$ for the specific radiometric measurements, values of $k_{\Im}(\lambda)$ could be considered as an alternative (i.e., $a(\lambda) \sim k_{\Im}(\lambda)$) In addition, in the absence of any experimental determination of the ratio $I_r(\lambda)$, its value can be estimated through theoretical simulations of atmospheric radiative processes.

Uncertainties

Main sources of uncertainty typical of in water radiometry data products are those resulting from environmental variability and corrections applied to data products (e.g., self-shading, anisotropy). The uncertainties resulting from environmental perturbations such as changes in illumination conditions, variability of the water optical properties during measurements, and wave perturbations, can be quantified from the standard deviation of subsurface values $\Im_0(0^-, \lambda)$ determined from the regressions of data from successive radiometric casts.

The quantification of uncertainties associated with self-shading are difficult for any radiometer system that cannot be idealized as a disk. So, in the case that dedicated computational studies are not available, best practice would suggest a large percentage (e.g., 25%) of the corrections be assigned to the uncertainties.

In the case of anisotropy corrections, their uncertainties may largely vary with the correction approach and the water type (Talone et al. 2018). It is thus suggested that in this case too, uncertainties account for a large percentage of the corrections.

Additionally it is important to consider the determination of radiometric uncertainties affecting derived products such as $R_{rs}(\lambda)$ and $L_{wn}(\lambda)$ resulting from the composition of different primary products. For example considering that $L_{wn}(\lambda) = L_w(\lambda) / E_d(\lambda) \cdot E_d(\lambda)$, it is evident that if both the E_d and L_u sensors are calibrated using the same basic source (e.g., a lamp), the systematic component of uncertainties affecting the source cancels out in the ratio. This element should be considered to avoid overestimates of the uncertainties(Johnson *et al.* 2014).

4. ALTERNATIVE METHODS

In addition to in-water profiling, an alternative in-water radiometric method is provided by the execution of measurements performed at fixed depths. This method is generally implemented through optical buoys specifically designed to host multiple radiometers (Clark *et al.* 1997, Antoine *et al.* 2009). These fixed-depth systems generally provide the capability of measuring $E_s(\lambda)$, and additionally $L_u(z_i,\lambda)$, $E_d(z_i,\lambda)$, and sometimes $E_u(z_i,\lambda)$, at two or more discrete depths z_i generally set between 1 and 10 m.

A major advantage of fixed-depth systems is the capability of producing a large number of data at each depth or long integration times, which helps minimizing the impact of wave perturbations through averaging or filtering. A main drawback is the need to implement corrections minimizing the impact of inelastic scattering, which mostly affects the red part of the spectrum or the effects of inhomogeneous vertical distributions of optically significant constituents between the depths of radiometers (Li et al. 2016). In fact, as opposed to profiling systems, the availability of measurements at two or three depths only, does not allow using regression methods minimizing the impact of a non-exact exponential decay with depth. Still, fixed-depth systems operated in oligotrophic waters can rely on a confident modelling of the in-water radiative processes to determine corrections (Voss et al. 2017). An additional element requiring attention is the need to prevent bio-fouling during deployment periods that may last several months.

An alternative in-water method is that based on floating systems equipped with a single L_u sensor operated near the surface and likely several E_d sensors at various depths to allow to determining the near surface attenuation coefficient (Zibordi *et al.* 2012). These systems, designed for manned operations, provide the advantage of allowing for the collection of a large number of $L_u(z,\lambda)$ values at a depth z close to the sea surface with the additional capability of accounting for the attenuation of the water below the sensor. The appreciable size of system components, however, requires dedicated computational efforts to determine self-shading corrections (Leathers *et al.* 2001).

5. FUTURE DIRECTIONS

A future objective of in-water profiling radiometry would be the definition of objective extrapolation schemes reducing the impact of subjective decisions, which, despite of the adoption of the same protocol, may lead to large uncertainties in data products.

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Chapter 5: Above-Water Radiometry Measurements and Data Analysis

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1. INTRODUCTION

Above-water radiometry is a valuable alternative to in-water radiometry for the determination of the water-leaving radiance $L_W(\lambda)$. During the last three decades, above-water radiometry has been a matter of extensive investigations leading to a number of alternative measurement methods. The general method presented in the following sections relies on the application of calibrated radiometers allowing for absolute spectral measurements of the total radiance from the sea surface $L_T(\theta,\phi,\lambda)$ (which includes contributions from $L_W(\lambda)$, sky–glitter and sun–glint) and of the sky $L_i(\theta',\phi,\lambda)$ (i.e., sky radiance), performed with observation geometries defined by the relative azimuth angle between sensor and sun ϕ, and the viewing angle θ specular to θ' (i.e., θ' =180- θ). An additional quantity required for the minimization of changes in illumination conditions during measurements and to compute the remote sensing reflectance $R_{RS}(\lambda)$, is the total downward irradiance $E_S(\lambda)$.

Recognizing the potentials for alternative methods such as those relying on plaques (Carder and Steward 1985, Rhea and Davis 1997, Sydor and Arnone 1997) or polarizers (Fougnie *et al.* 1999), their application is however considered challenged by field implementations (in the case of plaques) and by the application of comprehensive radiative transfer models (in the case of polarizers), which may affect the accurate quantification of the uncertainties of derived data products. Further, with reference to the number of alternative data processing solutions proposed in the literature mostly centered on the optimization of the sky-glint removal (i.e, the minimization of any residual sky radiance affecting $L_W(\lambda)$) (Lee *et al.* 1997, Gould *et al.* 2000, Ruddick *et al.*, 2006, Simis and Olsson 2013, Kutser *et al*. 2013), their effectiveness on data collected during clear sky conditions is not definitively proven. Because of this, considering that the objective of this work is focused on above-water radiometry for the validation of satellite ocean color radiometric data products naturally collected during clear sky conditions, the following sections will strictly rely on the basic measurement equation for above-water radiometry performed with calibrated radiometers and applicable for both autonomous and manned measurements (Mobley 1999).

2. MEASUREMENTS

Above-water radiometry relying on calibrated radiometers, requires measurements of the sky-radiance $L_i(\theta',\phi,\lambda)$ and total radiance from the sea $L_T(\theta,\phi,\lambda)$ performed at given geometries by ensuring minimization of superstructure perturbations such as shading and reflection effects or simply changes in the sea surface.

By following Mobley (1999), the measurement equation for the water-leaving radiance $L_w(\lambda,\theta,\phi)$ with measurement geometry determined by (θ, θ', ϕ) and sun zenith angle θ_0, is given by

$$L_w(\theta,\phi,\lambda) = L_T(\theta,\phi,\lambda) - \rho(\theta,\phi,\theta_0,W)L_i(\theta',\phi,\lambda) \quad (1)$$

where $\rho(\theta,\phi,\theta_0,W)$ is the sea surface reflectance factor (i.e., ρ-factor) with the wind speed W conveniently expressing the sea state.

Equation (1), however, describes a quite idealized measurement concept. In fact, the sky-radiance contributions to sky-glint may come from a portion of the sky around the direction (θ', ϕ) which varies with the degree of surface roughness. Further, the complexity of the sea surface resulting from the composition of gravity and capillary waves, in combination with parameters such as the instrument field-of-view and integration time, may challenge the capability of determining actual surface reflectance factors. Additional factors are the skylight polarization, and the interaction of this polarization with the sea surface. These elements are introduced and discussed in the following sub-sections with the objective of supporting a robust implementation of above-water radiometry.

Viewing geometry

The minimization of glint perturbations is the main challenge of above-water radiometry. Modelling (Mobley 1999) indicates that a viewing angle θ of 40° and a relative azimuth ϕ of 135° are the most appropriate to minimize sun glint perturbations. This geometry, however, often conflicts with practical limitations during field deployments. In fact, the use of $\phi = 135°$ may easily become the source of perturbations in $L_T(\theta,\phi,\lambda)$ measurements because the radiometer necessarily looks at the sea close to the deployment structure or at its shadow. This limitation, which becomes more severe with large sun zenith angles, would suggest that $\phi = 90°$ is a better solution despite the less favorable measurement conditions, which mostly occur at mid-high wind speeds (Zibordi *et al*. 2009).

It is thus emphasized that the viewing geometry results from tradeoffs between the measurement condition minimizing glint effects and those minimizing infrastructure impacts. Regardless of the applied geometry, it is relevant to point out that the non-nadir view characterizing above-water radiometry implies the removal of the viewing angle dependence, which requires the application of correction factors resulting from the application of models (e.g., Morel *et al* 2002). This additional element suggests that the adoption of a single viewing geometry, as opposed to the application of different geometries over time according to varying measurement conditions, would ensure higher consistency to data products.

Field-of-View

The field-of-view (FOV) of radiance sensors is not critical in determining $L_W(\lambda)$ from in-water profile data, because the (near-nadir) upwelling radiance distribution varies relatively little over nadir angles up to 10°. Conversely, in the case of above-water, the field-of-view is important for $L_i(\theta,\phi,\lambda)$ measurements because the sky-radiance is averaged over the instrument FOV. Still, when limiting the FOV for $L_i(\theta,\phi,\lambda)$ to within a few degrees (e.g., less than 10), its actual value is expected to have only a slight impact on the determination of $L_W(\lambda)$. Conversely, the high spatial and temporal variation of the slope distribution of the wind roughened sea surface (including effects by gravity and capillary waves) may have a large impact on $L_T(\theta,\phi,\lambda)$ data. In fact, a large FOV combined with long integration time (when applicable) may increase the averaging of wave effects. In contrast, a small FOV with short integration time (when applicable) would definitively increase the variability across successive measurements. Literature does not provide clear support on the selection of the most appropriate FOV. However, some investigation performed with multi-spectral radiometers operated with different fore optics allowing for alternative FOVs, appears to indicate preference for small FOV for $L_T(\theta,\phi,\lambda)$ measurements (tentatively less than 5°) and some flexibility for L_i (Hooker *et al*. 2004). Another study, solely based on theoretical simulations (Gilerson *et al.* 2018), suggests collecting $L_i(\theta',\phi,\lambda)$ data with a FOV which increases with seastate. An example of operational measurements performed with a 1.2° field-of-view for both $L_T(\theta,\phi,\lambda)$ and $L_i(\theta',\phi,\lambda)$ data is offered by the Ocean Color component of the Aerosol Robotic Network (AERONET-OC) (Zibordi *et al.* 2009). In this case the small FOV and the consequent variability in $L_T(\theta,\phi,\lambda)$ data are used to remove measurements affected by high variance and thus to filter those measurement conditions diminishing the accuracy of the surface reflectance factor (e.g., conditions often occurring with wind speed tentatively exceeding 7 m s^{-1} and sun zenith lower than 20°) (Zibordi *et al.* 2009, Zibordi 2012).

Finally, a high co-registration of the different spectral bands is the element ensuring that surface effects and consequently the sky-glint contributions reaching the sensor FOV, raise from the same area of the sea surface. This should discourage the application of filter-wheel radiometers in above-water radiometry because measurements are sequentially performed across the various bands. Actually, at the expense of inter-channel uncertainties, the example of AERONET-OC data shows that a severe quality control of measurements and quality assurance of products, allows $L_{WN}(\lambda)$ to be obtained with an accuracy comparable to that achievable with above-water systems which have more precise co-registration of spectral bands (Zibordi *et al.* 2012).

Avoidance of perturbations by deployment structures

As with in-water radiometry, $E_s(\lambda)$ measurements are essential. Perturbations by superstructures affecting $E_s(\lambda)$ measurements can only be avoided by deploying the radiometer above any obstacle that may be seen by the 2π field-of-view of the radiometer. Such a fundamental requirement is often challenged by the difficulty in reaching the highest locations of the deployment structures (e.g. ships), and the need to ensure daily maintenance to radiometers. A practical solution is often offered by the use of telescopic poles operated at convenient locations. It is finally noted that commercial systems may comprise L_T, L_i and E_s radiometers operating in compact configurations. These solutions, however, may prevent optimizing the deployment of the E_s sensor out of superstructure perturbing effects.

When considering $L_i(\theta',\phi,\lambda)$ and $L_T(\theta,\phi,\lambda)$, measurements should be made from a location that minimizes both shading and reflections from deployment structures. Generally, a good position for measuring the water-leaving radiance on ships is the bow. This, while steaming and with a suitable viewing geometry, ensures measurements with the water surface undisturbed by the ship wake or any associated foam. Major perturbations may result from an unfavorable deployment position with respect to the sun, which may lead to viewing an area of the sea surface too close to the superstructure itself. Experimental analysis showed that, as a rule of thumb, the viewed area should be located at a distance larger than the superstructure height (Hooker and Morel 2003, Hooker and Zibordi 2005). This finding, mostly resulting from measurements performed in the near-infrared, indicates that above-water radiometers should be operated on the uppermost locations of deployment structures in a place which views a surface area well away from superstructures themselves. In the case of fixed structures (e.g., towers or lighthouses), these requirements imply limiting the acquisition of measurements to within specific azimuth limits. In the case of ship measurements, the heading of the ship should be adjusted to warrant fulfillment of the previous distance requirements. In the case of autonomous shipborne measurements, the heading of the ship should be recorded together with the radiometric data to ensure a successive screening of those measurements not fulfilling the distance requirement.

Offsets recording

The dark signal of sensors generally exhibits a temperature dependence that can easily change with time as a function of operation and environmental conditions. In-air instrumentation often experience a much larger temperature range during measurements then in-water instruments. It is thus essential that each individual or sequence of measurements is accompanied by offsets determinations. Some commercial radiometers are equipped with shutters allowing for the automatic determination of the dark signal. In this case too, occasional measurements of the dark signal obtained by occulting the sensor fore optics would further support the quality assurance process.

Measurement sequence

Each measurement sequence should provide contemporaneous measurements of $E_s(\lambda)$, $L_i(\theta,\phi,\lambda)$ and $L_T(\theta,\phi,\lambda)$. Still, even though desirable, simultaneous measurements of $L_i(\theta,\phi,\lambda)$ and $L_T(\theta,\phi,\lambda)$ are not strictly necessary during clear sky conditions. Best practice suggests that each above-water determination of $L_w(\theta,\phi,\lambda)$ relies on successive measurements sequences (at least $L_i(\theta,\phi,\lambda)$ and $L_T(\theta,\phi,\lambda)$ in repeating sequences), each one restricted to within a very few minutes, but still each one producing a number of data suitable to investigate the stability of $E_s(\lambda)$ and $L_i(\theta,\phi,\lambda)$ and additionally the variability of $L_T(\theta,\phi,\lambda)$. It is emphasized that the collection of multiple measurement sequences further enables the quality assurance of data and are additionally essential to quantify the environmental perturbations affecting $L_w(\theta,\phi,\lambda)$.

Essential ancillary data

A number of ancillary data are required for the processing and eventually flagging of above-water radiometry measurements. Data essential for the comprehensive data processing of each measurement sequence include: date and time (UTC); longitude and latitude; cloud cover (likely supported by digital pictures or videos), and sea state; wind speed and direction, air and water temperature; barometric pressure. Quality control of data also requires that roll, pitch and heading of sensors are recorded in combination with the radiometric measurements in view of allowing removal of those data affected by excessive tilt effects and additionally to identify and remove those data likely affected by the deployment structure. It is specifically recalled that the attitude of sensors with respect to the vertical is a critical factor for the accuracy of $E_s(\lambda)$, and also of $L_i(\theta,\phi,\lambda)$ and $L_T(\theta,\phi,\lambda)$ measurements.

Finally, in view of supporting the implementation of future processing schemes relying on spectral sea surface reflectance factors, the aerosol optical properties including at least the optical depth should be measured. It should be noted that measurement of the aerosol optical depth is already a requirement for the computation of $E_s(\lambda)$ values when this is not actually measured.

3. DATA ANLYSIS

The data product from above-water radiometry is $L_w(\lambda)$. Its accuracy, in addition to the accuracy of calibration and characterization factors applied to radiometry data, largely depends on: i. the minimization of measurement artifacts resulting from elevated tilts; ii. the minimization of wave perturbations affecting $L_T(\theta,\phi,\lambda)$ data; iii. the accuracy of ρ-factors; iv. the accuracy of the correction applied for the minimization of the off-nadir view (i.e., anisotropy effects). This section provides basic elements in the processing of $L_i(\theta,\phi,\lambda)$, $L_T(\theta,\phi,\lambda)$ and $E_s(\lambda)$ to determine $L_w(\lambda)$.

Offset removal, corrections for the non-ideal performance of sensors and calibration

The instrument offset in each channel must be subtracted from the raw field data prior to any further processing. Successive steps are the application of any correction minimizing the non-ideal performance of the radiometer in combination with the application of the absolute calibration coefficients accounting for pre- and post-field laboratory calibrations, and eventually supplementary field stability checks performed with portable reference sources.

As already pointed out for in-water methods, these early data reduction steps suggest the need for efficient access to any information required for the processing and successive re-processing of field measurements. This should imply a data management system ensuring unique association of raw field data to measurement campaigns, stations, casts, essential ancillary data and, obviously, radiometer tags and their calibration coefficients and correction factors.

Quality control of data

A number of quality checks need to be implemented to remove data that may affect the accuracy of above-water data products (Zibordi *et al*. 2009). Quality checks should first allow removing data affected by excessive tilts (ideally any data affected by tilts higher than a very few degrees). Tilt thresholds should generally result from tradeoffs between the need to preserve a significant number of data and their quality. Thresholds may vary slightly across deployment platforms and sea state.

Additional quality checks should remove those measurement sequences affected by any significant variability of $E_s(\lambda)$, $L_i(\theta,\phi,\lambda)$ and $L_T(\theta,\phi,\lambda)$ not explained by tilt perturbations. Specifically, with the overall requirement of clear sun and low cloudiness, it is fundamental the $L_i(\theta,\phi,\lambda)$ measurements are not affected by clouds directly seen by the sensor or located in its immediate vicinity (in fact bright clouds occurring in the close vicinity of the portion of sky observed by the L_i sensor could induce significant adjacency effects in measurements). Thus, quality checks applied to $E_s(\lambda)$ and $L_i(\theta,\phi,\lambda)$ should aim at removing those measurement sequences likely contaminated by clouds. These checks should rely on very small thresholds (ideally a very few percent change of the measured signal). Checks on $L_T(\theta,\phi,\lambda)$ data should lead to the removal of those measurement sequences heavily affected by sun-glint and likely foam perturbations in addition to excessive sky-glint contributions from bright portions of the sky. In such a case, a practical solution is offered by the use of statistical indices such as the standard deviation to remove those measurement sequences exhibiting values exceeding thresholds. These thresholds are instrument specific, being a function of FOV and integration time: a large FOV or a high integration time lead to the averaging of glint and any additional surface perturbations.

Finally, quality checks should apply to differences between the pre- and post-field calibrations of optical sensors. This step may largely benefit from field checks performed with portable reference sources. Thresholds in calibration differences should obviously account for the deployment duration and the working conditions. When considering well-maintained systems (e.g., regularly cleaned) and deployed for a short time (e.g., up to a few weeks), differences between pre- and post-field calibrations should be mostly explained by calibration uncertainties. Slightly larger differences due to actual sensitivity decay with time, may require actions such as interpolations between calibrations. Large unexplained differences, which may challenge the determination of accurate radiometric products, should lead to the rejection of the measurement sequence.

Normalization by Surface Irradiance

Similar to in–water data, the individual measurements of $L_T(\theta,\phi,\lambda)$ and $L_i(\theta',\phi,\lambda)$, should be corrected for illumination changes using the corresponding $E_s(\lambda)$ values. By restating the requirement of clear sun and low cloudiness, and introducing the time dependence t for measurements, changes in the illumination conditions likely only due to changes in the sun position, are minimized through measurements of $E_s(\lambda,t)$ performed simultaneously to the collection of $L_i(\theta,\phi,\lambda,t)$ and $L_T(\theta,\phi,\lambda,t)$.

In agreement with the scheme proposed for in-water radiometry, using $\Im(z, \lambda, t)$ to indicate both $L_i(\theta,\phi,\lambda,t)$ and $L_T(\theta,\phi,\lambda,t)$

$$\Im_0(\theta,\phi,\lambda,t_0) = \frac{\Im(\theta,\phi,\lambda,t)}{E_s(\lambda,t)} E_s(\lambda,t_0) \quad (2)$$

where $\Im_0(\theta, \phi, \lambda, t_0)$ is the radiometric quantity normalized to the incident light field at t_0, $E_s(\lambda, t_0)$, with t_0 reference time pertaining to the measurement sequence (e.g., the start of the sequence).

Again, it is important that there be a close match between the spectral bands of the E_s sensor and those of the radiance sensors to avoid introducing spectral artefacts in the normalized data.

Finally, if $E_s(\lambda)$ measurements are not available, the above-water method described is considered still effective during stable illumination conditions when the measurement sequences are restricted to within a very few minutes, albeit at the expense of an increase in uncertainties (Zibordi *et al.* 2009).

Sea Surface Reflectance Factor

The sea surface reflectance ρ is defined by the total sky-radiance reflected into the FOV of the L_T sensor from the wave-roughened sea surface in the direction (θ,ϕ), divided by sky-radiance into the L_i FOV from the direction (θ',ϕ). Noting that the values of $\rho(\lambda)$ are obtained from simulations, their capability to predict the actual sea surface reflectance characterizing measurements is dependent on the capability to model the surface features and the light contribution reflected into the L_T FOV (including sky radiance from a variety of zenith and azimuth angles, which add to sun-glint or foam contributions) characterized by time scales varying from milliseconds to seconds (as a function of the integration time) and spatial scales varying from a few to several tens of cm^2 as (as function of the FOV and sensor altitude above the sea surface).

The most commonly used values of ρ (Mobley 1999) were determined from simulations performed at $\lambda = 550$ nm, accounting for the dependence on the viewing and illumination geometries, and modelling the effects of sea state as a function of wind speed through the Cox-Munk parameterizations. The sky radiance distribution was obtained from an irradiance model and experimental sky radiance patterns. While multiple scattering and aerosol effects were implicitly accounted for, the polarization effects were neglected.

As a result of a number of investigations indicating non negligible impact of polarization effects (Harmel *et al.* 2012, Mobley 2015, Hieronymi 2016, D'Alimonte and Kajiyama 2016, Foster and Gilerson 2016, Gilerson *et al.* 2018), new reflectance factors at $\lambda = 550$ nm were recently proposed accounting for the wave height and slope variance, in addition to polarization effects (Mobley 2015). As opposed to previous values of ρ, the new ones were determined for a clear purely molecular (i.e., Rayleigh) sky with single scattering approximation. Consequently, this specific ideal case can be considered as representative of extreme polarization effects because of the absence of depolarization effects from aerosols.

The two sets of ρ factors exhibit marked differences as a function of the viewing and illumination geometries as well as wind speed. When considering measurements performed with low wind speed and away from low sun zeniths, experimental assessment of the two sets of factors indicated slightly better performance for those determined neglecting the polarization effects (Zibordi 2016). Accounting for this finding and for investigations pointing out the relevance of aerosol contributions and ultimately the non-negligible spectral dependence (Lee *et al.* 2010, Gilerson *et al*. 2018), it is suggested that the operational processing of above-water radiometry data still rely on the ρ factors computed neglecting polarization effects (e.g. Mobley 1999). Obviously, spectral values of ρ factors comprehensively accounting for polarization effects as a function of aerosol type and load should be applied as soon as available and verified.

Determination of L_w

The $L_T(\theta,\phi,\lambda)$ and $L_i(\theta',\phi,\lambda)$ values applied for the computation of $L_w(\theta,\phi,\lambda)$ through Eq. 1 should be obtained from the averaging of *n*-independent measurements satisfying filtering criteria to remove those individual $L_T(\theta,\phi,\lambda)$ values affected by significant glint and foam perturbations.

A number of investigations showed the benefit of using the mean of $L_T(\theta,\phi,\lambda)$ relative minima determined from a percentage of the quality checked ones (Zibordi *et al.* 2002, Hooker *et al.* 2002). This solution further minimizes the impact of values affected by significant glint and foam contamination in the quality checked measurement sequences.

The number of values to be averaged may range from a few up to ten of percent of the available data dependent on instrument characteristics such as FOV and integration time and the data collection scheme.

It is important to remember that the proposed averaging of $L_T(\theta,\phi,\lambda)$ values relying on relative minima collected during the measurement sequence, may lead to an underestimate of the sky-glint correction (Zibordi *et al.* 2009, Zibordi 2012). However, this may only have significant impact for data collected with high sea state and low sun zenith angles, which are conditions generally removed by quality checks applied to individual measurement sequences.

The averaging of $L_i(\theta',\phi,\lambda)$ data for each measurement sequence should not undergo any restriction, given clear sky conditions. However, in the case of simultaneous of $L_T(\theta,\phi,\lambda)$ and $L_i(\theta',\phi,\lambda)$ measurements, the averaging of $L_i(\theta',\phi,\lambda)$ data should be performed using those measurements corresponding to those applied for the determination of the $L_T(\theta,\phi,\lambda)$ mean value.

Quality assurance of data

The quality assurance should largely focus on data products i.e., $L_w(\lambda)$ or $L_{wn}(\lambda)$, exhibiting negative values (not explained by uncertainties) indicating over-correction of the sky glint contribution, or exhibiting excessively high values in the near infrared as a result of under-correction of sky glint perturbations or a large impact of sun-glint, foam or even of the deployment superstructure.

Corrections for non-nadir view

It is essential to recall that $L_w(\lambda,\theta,\phi)$ is determined for a non-nadir view, which implies the need to remove the viewing angle dependence. This is achieved through

$$L_w(\lambda) = L_w(\theta,\phi,\lambda)\frac{\Re_0}{\Re(\theta,W)}\frac{Q(\theta,\phi,\theta_0,\lambda,\tau_a,IOP)}{Q_n(\theta_0,\lambda,\tau_a,IOP)} \quad (3)$$

where the ratio of $\Re_0$ (i.e., $\Re(\theta,W)$ at $\theta=0$) to $\Re(\theta,W)$ accounts for changes in surface reflectance and refraction, and the ratio of $Q(\theta,\phi,\theta_0,\lambda,\tau_a,IOP)$ to $Q_n(\theta_0,\lambda,\tau_a,IOP)$, i.e., the Q-factors at viewing angle θ and at nadir (i.e., $\theta = 0$), minimize the effects of the anisotropic radiance distribution of the in–water light field as a function of the water *IOP*s, the observation and illumination geometries defined by θ, ϕ and θ_0, and the atmospheric optical properties conveniently by the aerosol optical depths τ_a during clear sky conditions.

In Case-1 waters (i.e., waters where the optical signal is determined by phytoplankton), the IOPs can be solely expressed as a function of the chlorophyll-*a* concentration, *Chla*. For this specific case, tabulated values of $\Re(\theta,W)$ and of the Q-factors were produced through simulations (Morel *et al.* 2002). It is anticipated that, for actual computations, the ratio $Q(\theta,\phi,\theta_0,\lambda,\tau_a,Chla)/Q_n(\theta_0,\lambda,\tau_a,Chla)$ needs to be replaced by actually available values of $f(\theta_0,\lambda,\tau_a,Chla)/Q(\theta,\phi,\theta_0,\lambda,\tau_a,Chla)$ and $f(\theta_0,\lambda,\tau_a,Chla)/Q_n(\theta_0,\lambda,\tau_a,Chla)$. This exchange of quantities is supported by the fact that $f(\theta_0,\lambda,\tau_a,Chla)$, which relates the irradiance reflectance to *IOP*s through the ratio of backscattering to absorption coefficients, does not depend on θ. It is finally mentioned that the dependence on τ_a of both $Q(\theta,\phi,\theta_0,\lambda,\tau_a,Chla)$ and $f(\theta_0,\lambda,\tau_a,Chla)$, is small with respect to that of the other quantities. Because of this, the tabulated values of $Q(\theta,\phi,\theta_0,\lambda,\tau_a,Chla)$ and $f(\theta_0,\lambda,\tau_a,Chla)$ are currently only provided for a maritime aerosol with optical depth τ_a=0.2 at 550 nm.

An alternative correction approach for bidirectional effects applicable to both Case-1 and optically complex waters has shown the advantage of not requiring any additional input other than the measured $L_w(\theta,\varphi,\lambda)$ (Lee *et al*. 2012). This approach relies on the following equation to determine the inherent optical properties from $L_w(\theta,\varphi,\lambda)$

$$L_w(\theta,\phi,\lambda) = E_s(\lambda)\left\{\left[G_0^w(\theta,\phi,\theta_0) + G_1^w(\theta,\phi,\theta_0)\cdot\frac{b_{bw}(\lambda)}{k(\lambda)}\right]\cdot\frac{b_{bw}(\lambda)}{k(\lambda)} + \left[G_0^p(\theta,\phi,\theta_0) + G_1^P(\theta,\phi,\theta_0)\cdot\frac{b_{bp}(\lambda)}{k(\lambda)}\right]\cdot\frac{b_{bp}(\lambda)}{k(\lambda)}\right\} \quad (4)$$

where the coefficients G_0^w, G_1^w, G_0^p, G_1^p are the model parameters, b_{bw} and b_{bp} the pure sea water and particle backscattering coefficients, respectively, with k=a+b_b and b_b=b_{bw}+b_{bp}, and a total seawater absorption coefficient. Once the values of a and b_b are derived, their value is applied to calculate $L_w(\lambda)$ by applying the parameters G_0^w, G_1^w, G_0^p, G_1^p for θ=0 through

$$L_w(\lambda) = E_s(\lambda)\left\{\left[G_0^w(0,0,\theta_0) + G_1^w(0,0,\theta_0)\cdot\frac{b_{bw}(\lambda)}{k(\lambda)}\right]\cdot\frac{b_{bw}(\lambda)}{k(\lambda)} + \left[G_0^P(0,0,\theta_0) + G_1^P(0,0,\theta_0)\cdot\frac{b_{bp}(\lambda)}{k(\lambda)}\right]\cdot\frac{b_{bp}(\lambda)}{k(\lambda)}\right\} \quad (5)$$

An evaluation of the two correction approaches (Gleason *et al.* 2012) indicated a superior performance of the first method in Case-1 waters and conversely of the second one in optically complex waters. An analysis of the uncertainties affecting corrections determined for the latter approach applicable to optically complex waters, indicated relative uncertainties for corrections varying in the range of 20-35% independent from wavelength and water type (Talone *et al.* 2018).

Uncertainties

Key uncertainties affecting above-water radiometric measurements are those associated with environmental perturbations, the accuracy of the sea surface reflectance factors and the corrections for non-nadir view.

Uncertainties due to environmental perturbations can be quantified from the standard deviation of $L_w(\lambda)$ values determined from consecutive measurement sequences. These uncertainties would embrace effects of changes in the illumination conditions, water type and mostly wave perturbations.

The determination of the uncertainties affecting the surface reflectance factors and corrections for non-nadir view would require comparisons with in situ reference measurements performed with alternative methods (e.g., in water radiometry). Because of this, their actual determination is objectively difficult and may alternatively rely on published data. Still, at least the precision of the applied reflectance factors and corrections should be investigated by evaluating the impact of the accuracy of the input parameters.

4. ALTERNATIVE METHODS

A number of methods have been proposed and applied for the determination of $L_w(\lambda)$ from above-water radiometry. These include the use of plaques, which provide the major advantage of operating with non-calibrated radiometers (Carder and Steward 1985, Rhea and Davis 1997, Sydor and Arnone 1997). This approach requires viewing the plaque with the radiance sensor, alternatively applied to gather the radiance from the sky and sea, with geometry equivalent to that detailed in the previous sections.

An alternative method relies on the combination of polarized measurements of the radiance from the sea and modelled sky-radiance computed with the aid of measured values of the aerosol optical depth (Fougnie *et al.* 1999). This method has the advantage of highly reducing the sky-glint by measuring only the vertically polarized component of $L_T(\theta,\phi,\lambda)$ and consequently minimizing the dependence of measurements from the reflectance of the sea surface. The accuracy of the method, however, largely depends on the capability of accurately modelling the residual sky-glint radiance and accounting for the non-zero polarization of $L_w(\lambda)$.

A further alternative method is the skylight-blocked approach (Tanaka *et al.* 2006, Lee *et al.* 2010, Lee *et al.* 2013). This method leads to the direct measurement of the water-leaving radiance $L_w(\lambda)$ from a sensor operated just above the water surface. Unique to the method is a screen blocking the skylight around the radiance sensor. This approach does not require any knowledge of the sea surface reflectance, still, it requires self-shading corrections (Lee *et al.* 2013, Shang *et al.* 2017).

5. FUTURE DIRECTIONS

A number of inter-comparisons between data products from in-water and above-water methods have been proposed during the last two decades (e.g. Toole *et al.* 2000, Hooker *et al.* 2004, Zibordi 2016). These clearly show major incremental improvements in both the practice and understanding of above-water radiometry. For instance, recent comparisons of $L_w(\lambda)$ and $L_{WN}(\lambda)$ products performed during clear sky conditions, amply illustrates the equivalence of above- and in-water measurement methods (Zibordi 2012) with differences fully explained by the combined uncertainties assigned to the data products. Still, it is fundamental to continue producing accurate in situ measurements through alternative approaches relying on state-of-the-art methods and technology, to further explore uncertainties affecting above-water data products and provide evidence of new advances.

When considering specific investigations relevant for above-water radiometry, a number of issues still require attention. These include: exploring the impact of FOV; the application of filtering schemes to $L_T(\theta,\phi,\lambda)$ supported by objective criteria likely function of sun zenith and wind speed; more extended analysis on the impact of superstructures on $L_T(\theta, \phi, \lambda)$; and finally producing ρ spectral factors which fully account for polarization effects, slope and wave height, multiple scattering and, aerosol type and load.

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