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Abstract

A high calibration accuracy of *in situ* radiometers is fundamental for the application of in situ measurements to the vicarious calibration of ocean color space data and the validation of remote sensing radiometric products. Key calibration term of any in-water radiometer is the immersion factor: the coefficient which needs to be applied to in-air absolute calibration factors to account for sensor's sensitivity changes when operated in-water. The current document outlines the methodologies which should be applied to determine immersion factors for both radiance and irradiance underwater sensors.

Introduction

The absolute calibration of underwater light sensors is generally performed in air using a standard source. Because of this the calibration of data collected in water requires the application of multiplication coefficients, the so–called immersion factors, to account for the change in the sensors' response due to the different refractive index of the intervening medium (i.e., seawater) in contact with the optics. In the case of in–water irradiance sensors the change in the absolute response is primarily caused by a change in the reflectance and transmittance of the water–collector with respect to the air–collector interface. In the case of in–water radiance sensors, the change in the in–water measurements with respect to in–air is mostly due to a change in the solid angle field of view and in the reflectance and transmittance of the water–optics with respect to the air–optics interface.

Referring to the calibration equation and omitting the wavelength dependence, the spectral radiance or irradiance of a target source, $\Re$, is related to the radiometric measurement DN of a sensor looking at the target by

$$\Re = C_c I_f DN \tag{1}$$

where C_c is the spectral calibration coefficient determined in the laboratory through the in–air absolute radiometric calibration and I_f is the spectral immersion factor. The measurement DN (in relative units) is obtained by subtracting the background or alternatively the dark signal, from the sensor output obtained when looking at the target. The value of I_f is then equal to 1 for in–air measurements and it is greater than 1 for in–water measurements. Thus, this latter value corrects for the change of the sensor's radiometric response due to the spectral refractive index of water n_w which is greater than that of air n_a.

The accuracy of in situ radiometric measurements has great relevance in the use of ocean colour for the vicarious calibration of space data and the validation of radiometric products resulting from the atmospheric correction of top-of-the-atmosphere radiances. Some space agencies have defined a maximum uncertainty target of 5% for the atmospherically corrected radiances (McClain et al. 2004). This means that when vicarious calibration processes are applied (i.e., the space sensor is indirectly calibrated using *in situ* data), or when the accuracy of space derived products is assessed, the overall uncertainty budget of *in situ* measurements must be below 5%. This is only possible when each source contributing to the overall uncertainty budget (i.e., calibration uncertainty, deployment perturbations and environmental variability) lead to individual uncertainties much lower than 5%. Because of this, the quantification of the uncertainty and when possible the maximization of the accuracy of I_f values for in–water radiometers must be considered a requirement, or at least a good practice, within the framework of ocean colour investigations.

Background

Studies on the experimental characterisation of the immersion factor I_f, for different series of in–water irradiance sensors were presented in Mueller (1995) and in Zibordi et al. (2004). These studies showed a significant variance in I_f from different sensors pertaining to two commercial series of instruments. Specifically, Mueller (1995) presented experimental I_f values for twelve irradiance multi-spectral radiometers equipped with single diffusers (i.e., each one serving multiple spectral channels) and pertaining to the same series of underwater instruments. The determination of I_f was made with an uncertainty of approximately 1% and showed a dispersion ranging between 3% and 5% (defined by 1 standard deviation, σ) with differences as large as 10% across the various radiometers. This result first suggested the need for experimental characterisation of each individual irradiance sensor as a requirement for accurate in–water measurements. The work of Zibordi et al. (2004) presented the characterisation of nine seven-channel irradiance sensors. These belonged to the same series of radiometers and were equipped with multiple collectors (i.e., each one serving a single channel). The values of I_f were determined with an average repeatability (quantified as twice the percent variation coefficient of multiple characterisations of the same radiometer) better than 0.6 % and exhibited an average dispersion of 2% (determined by 2σ) with individual spectral values as high as 5% across the different radiometers. These results further confirmed the need for a full spectral characterisation of each radiometer for an accurate determination of in–water irradiances.

Unlike immersion factors of irradiance sensors which can only be determined experimentally, I_f values for radiance sensors are commonly derived theoretically. A general model, usually applied for the computation of I_f for radiance sensors, was proposed by Austin (1976). This model simply relies on the knowledge of the refractive indices of seawater and of the radiometer's window in contact with the intervening medium (i.e., air or seawater). The alternative possibility of experimentally characterizing I_f for radiance sensors was recently documented by Zibordi (2005). His study focused on a specific class of underwater multi-aperture instruments and showed the possibility of determining I_f with an uncertainty of 0.2%. For the considered class of radiometer, the study reported an average spectral bias of approximately –0.4% in the theoretical determination of I_f using Austin's model with respect to its experimental characterisation. This analysis, restricted to a few radiometers, did not show any appreciable instrument to instrument dispersion of the I_f values (i.e. it was typically within 0.1%). One conclusion was that the theoretical determination of I_f for the considered class of multi-spectral radiometers is sufficiently accurate for most of the applications. Additional analysis

(Zibordi and Darecki, 2006) based on radiometers with different optics design, showed that the difference between I_f determined experimentally and computed with the basic equation may become quite large (i.e., of the order of a few percent). This suggests that the experimental characterization of I_f for sample radiance sensors of each series should become part of their quality assurance process to assess the deviation of the immersion factor from its theoretical determination.

Measurement method for Irradiance Sensors

Experimental I_f values for irradiance sensors can be determined in agreement with the laboratory setup and the measurement method presented in Zibordi et al. (2003) and discussed in Hooker and Zibordi (2005). In summary the measurement setup is composed of an optical bench used to support a water vessel, a light source (a 1,000W tungsten-halogen lamp) and light baffles to minimise the light cone illuminating the sensor. The water vessel, the so–called CoMPACT (Compact Portable Advanced Characterisation Tank), is composed of a cylindrical tank 45 cm long with approximately 10 cm internal diameter, whose bottom is shaped to accommodate the radiometers. The interior of the tank is lined with knife-edge baffles spaced 2.5 cm apart. Tapped holes, spaced 5 cm apart, provide control of the water level. All components of the ComPACT unit are dull black to minimise reflections (this is a relevant element when considering the small diameter of the tank whose internal walls could reflect light). The lamp is powered with a regulated power supply. A precision shunt resistor in series with the lamp is used to monitor the stability of the light source.

The value of I_f is determined with irradiances measured by the radiometer in air and just below the water surface using the proposed measurement setup. The various steps required for producing the specific measurements are the following:

1. Align and level the measurement system (lamp, lamp-screen, water vessel).
2. Power on the lamp and warm-up.
3. Install the radiometer at the bottom of the water vessel with the apertures facing the source.
4. Collect dark data by temporarily covering the aperture of the water vessel.
5. Collect the in-air data with the diffuser completely dry.
6. Fill the tank with pure water.
7. Remove any air bubbles on the face of the radiometer and on the edge of the baffles.
8. Decrease the water depth in the tank by a decrement Δz=5 cm using the drain hole below the current water level.
9. Collect data from the in-water radiometer.
10. Repeat steps 8 and 9 until data are collected with the lowest water depth.
11. Remove the radiometer and dry the inner components of the tank.

The lamp and shunt voltages are regularly recorded at step 9 to detect changes in the lamp power which may affect the measurement sequence. The water temperature is also recorded during the measurement sequence to determine the water refractive index more precisely.

Each individual in–air or in–water measurement is obtained by averaging sequential observations corrected for the dark signal.

The immersion factor I_f, without making explicit the wavelength dependence, is determined from

$$I_f = \frac{E(0^+)}{E(0^-)} t_{wa} \qquad 2$$

where $E(0^+)$ is the in–air irradiance, $E(0^-)$ the in–water subsurface irradiance and t_{wa} the transmittance of the air-water interface. The latter is computed from the Fresnel reflectance for a vertically incident light beam. The value of $E(0^-)$ is determined from the least square fit —as a function of the water level above the sensor — of the log transformed of in–water measurements computed with I_f=1 and corrected for the geometric perturbation induced by the finite distance between source and irradiance sensor. This perturbation creates a flux change at the collector surface as a function of the water depth and source-collector distance (Zibordi et al. 2004).

The traceability of the experimental I_f values should be granted by the use of Milli-Q water replaced after each radiometer characterisation. The values of water refractive indices applied for the data analysis (i.e., for computing t_{wa} and determining the geometric correction of in–water data due to the finite distance between source and collector) can be those proposed by Austin and Halikas (1976).

Measurement method for Radiance Sensors

Experimental values of I_f for radiance sensors can be determined applying the setup and the method presented and discussed in Zibordi (2005). Specifically, the measurement setup is composed of a water vessel made of Plexiglas (having height, width and length of 35, 33 and 30 cm, respectively) with the lateral walls internally screened with a cylindrical tube painted dull black (so–called blackened screen), a support to hold the radiometer within the vessel with the optics facing the source and a diffuse light source constituted of a diffuser located in air just underneath the water vessel illuminated from below by a 1000 W tungsten-halogen lamp. The diffuser is made of a multilayer of white flashed opal glasses manufactured by Shott AG (Grünenplan, Germany). The lamp is screened to reduce the background light, and an adjustable aperture is used to optimize the size of the light cone illuminating the diffuser. The lamp is powered with a regulated power supply. The stability of the source is tracked by monitoring the voltages across its terminals and across a precision shunt in series with it. The water depth is read by means of a ruler fixed inside the vessel and located between the Plexiglas wall and the blackened screen.

The method for the experimental determination of I_f for radiance sensors relies on in–water and in–air radiance measurements of a stable, homogeneous and Lambertian source virtually immersed in the water, performed keeping the sensor–source distance constant with the sensor looking vertically at the source. Specifically the different steps required to produce the needed measurements are the following:

1. Align and level the measurement system (lamp, lamp-screen, water vessel and instrument support).
2. Power on the lamp and warm-up.
3. Install the radiometer in its mechanical support above the water vessel with the apertures facing the source.
4. Fill the vessel with pure water until the optics of the radiometer (i.e., the window) is immersed.
5. Remove any bubbles entrapped in front of the window.

6. Collect the in–water data.
7. Decrease the water level by a decrement $\Delta z = 2$cm below the optical window, remove the radiometer, dry the optical window and restore the radiometer in its support.
8. Collect the above-water data.
9. Lower the water level by a decrement Δz.
10. Repeat steps 7 and 8 for successive decrements Δz of the water level.
11. Collect the background data by covering the aperture of the lamp screen.

The lamp and shunt voltages are regularly recorded at steps 6 and 8 to identify changes in the lamp power which may affect the measurement sequence. The water temperature is also recorded during the measurement sequence.

Each individual in–air and in–water measurement is determined by averaging sequential observations corrected for the background signal.

Without making the wavelength dependence explicit, I_f is determined from

$$I_f = \frac{L(0^+)}{L(0^-)} \frac{\Omega_a}{\Omega_w} \frac{1}{t_{wa}(\Omega_w)} \qquad 4$$

where $L(0^+)$ is the above–water value, computed as the intercept of the least squares regression — as a function of the distance of the sensor from the water surface — of in–air measurements made with different water levels and corrected for the different air–water optical paths (Zibordi 2005). The term $L(0^-)$ is the spectral in–water radiance determined from measurements taken with the instrument immersed in the water and computed with I_f=1. The terms Ω_a and Ω_w indicate the solid angle field of view in air and in water, respectively. The term $t_{wa}(\Omega_w)$ indicates the water–air transmittance averaged over the solid angle Ω_w.

The values of I_f should be characterised with Milli-Q water to perform measurements in a very reproducible manner and to use a medium with well-defined optical properties (i.e. refractive index).

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