Response to Temperature of a Class of In Situ Hyperspectral Radiometers

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ABSTRACT

The response to temperature of sample hyperspectral radiometers commonly used to support the validation of satellite ocean color data was characterized in the 400–800-nm spectral range. Measurements performed in the 10°C–40°C interval at 5°C increments showed mean temperature coefficients varying from \(-0.04 \times 10^{-2} \, (^\circ C)^{-1}\) at 400 nm to \(+0.33 \times 10^{-2} \, (^\circ C)^{-1}\) at 800 nm, which are largely explained by the temperature coefficient of the photodetector array constituting the core of the sensor. Overall, the results indicate the possibility of applying temperature corrections with an uncertainty of approximately \(0.03 \times 10^{-2} \, (^\circ C)^{-1}\) for the class of hyperspectral radiometers investigated in the study.

1. Introduction

The responsivity of optical radiometers is affected by the temperature sensitivity of its components (Starks et al. 1995). For instance, temperature can significantly affect the spectral response of silicon photodiodes in the near-infrared (Hartmann et al. 2001) or induce changes in the center wavelength and bandwidth of interference filters (Basher and Matthews 1977). To a lesser extent, temperature may also affect optics, electronics, and mechanical components. Because of this, best practice would suggest the use of thermally stabilized radiometers when highly accurate measurements are required. Alternatively, in the absence of thermal stabilization, the characterization of the response to temperature of each radiometer or at least of samples for each class of radiometers is highly recommended (Schaepman and Dangel 2000; Salim et al. 2011).

The objective of this work is the determination of the response to temperature of sample units of hyperspectral radiometers widely applied by the scientific community to support satellite ocean color validation activities. The work finds its rationale in the need to ensure accurate quantification of uncertainties affecting in situ radiometric measurements and to investigate solutions for their minimization.

2. Radiometers characterization

The temperature response of the broadly used RAMSES hyperspectral radiometers (Zibordi et al. 2012) has been determined for a few sample units. These radiometers are manufactured by TriOS Mess-und Datentechnik GmbH (Rastede, Germany) and built on ZEISS (Oberkochen, Germany) Monolithic Miniature Spectrometers (MMS-1). The spectrometers, which rely on the Hamamatsu (Ichino-cho, Japan) S3904 256-channel silicon photodiode array coupled to a concave image grating, have a spectral resolution of approximately 10 nm in the 320–950-nm interval with an average spectral sampling of 3.3 nm. The optics of RAMSES ARC radiance sensors is composed of an optical window and a lens coupled to the fiber bundle supplying light to the spectrometer. The distance between the lens and the fiber bundle is set to delimit a 7° full-angle field of view. In the case of RAMSES ACC irradiance sensors, a cosine collector is coupled to the fiber bundle. The optics, spectrometer, and electronics are enclosed in a steel case.

Silicon photodiodes exhibit a response to temperature moderately increasing toward the blue-green spectral...
region but largely increasing with wavelength in the near-infrared (McCluney 2014). RAMSES radiometers, similar to most field radiometers, are not thermally stabilized. Field radiometers are calibrated in a controlled environment (e.g., at 20°C), but they are operated at temperatures widely changing with location, season, and measurement conditions. Because of this, the response to temperature may become the source of unpredictable uncertainties often not included in uncertainty budgets.

The characterization of temperature coefficients of a radiometer implies the capability to accurately measure the response to temperature changes of the device under test. Details on the laboratory setup, measurement protocol, and data reduction scheme applied to determine the temperature coefficients of RAMSES radiometers are provided in the following subsections.

a. Laboratory setup and measurement protocol

The temperature coefficients of RAMSES were determined by operating the radiometers in a temperature-controlled tank (TC-Tank) while looking at a stable source. A schematic of the measuring system is displayed in Fig. 1.

The TC-Tank is composed of two fully independent compartments made of aluminum. The internal compartment hosts the radiometer (either a radiance or irradiance sensor) together with a thermistor and a humidity sensor. Conversely, the external compartment is filled with water whose temperature is regulated through a Haake G/D1 controller from Haake Mess-Technik (Karlsruhe, Germany). The tank has an optical window allowing access to an external source (i.e., the flux from an integrating sphere or from a lamp). The optical window is composed of a flange mount collar hosting a fused silica window or, alternatively, a white glass diffuser. The former is used for the characterization of irradiance sensors, while the latter is operated with radiance sensors to increase the homogeneity of the flux filling the field of view.

An aluminum adapter in contact with the internal walls of the tank hosts the radiometer and in its vicinity, both the thermistor and the humidity sensor. The adapter, which allows accurate mechanical alignment of the radiometer optics with respect to the axis of the optical window, maximizes thermal conductivity among the various components of the system.

A reduction of stray light inside the TC-Tank is obtained by limiting the illuminated volume through an adjustable diaphragm positioned on the flange. Finally, a resistor wrapped on the flange heats the optical window to avoid formation of moisture on its surfaces (e.g., at the room temperature of approximately 20°C, the resistor can produce an increase in temperature up to approximately 10°C at the surface of the flange in close contact with it). A Spectralon integrating sphere manufactured by Labsphere (North Sutton, New Hampshire), with 6.3-cm aperture and an internal tungsten halogen 100-W lamp powered with 8.33 A, was used as a light source for the characterization of RAMSES radiometers. The sphere, when compared to lamps, offers the practical advantage of a relatively easy adjustment of the source-tank distance during characterizations.

Radiometric measurements of the light source were performed after aligning the optical axes of the sphere, TC-Tank window, and radiometer, with a variable distance of 5–25 cm between the sphere and the tank. A thermal insulating screen located between the aperture of the sphere and the optical window of the tank prevented heat transfer between the two components of the measuring system while radiometric data were not collected.

FIG. 1. Schematic of the measuring system. Optical window comprises a fused silica window (or a white glass diffuser) and an adjustable diaphragm. Adapter, hosting a thermistor and a humidity sensor, ensures accurate alignment of the radiometer optics with respect to the axis of the optical window. Thermal insulating screen, which is operated to avoid heat transfer from the integrating sphere to the TC-Tank, is removed only for the duration of measurements. Inlet and outlet allow the flow of water at controlled temperature in the external compartment of the tank.
Considering that RAMSES radiometers do not have an internal thermistor, the temperature $T$ of the internal chamber of the TC-Tank, hereinafter called ambient temperature, was used to determine the temperature coefficient of radiometers.

After warming up the source and setting the temperature of the tank to values close to 5°C, each characterization comprised sequential measurements performed in 5°C increments in the 10°–40°C interval when the thermal equilibrium was ideally reached inside the tank. Practically, data were collected at intervals of approximately 60 min (even though for some radiometers, mostly for verification purposes, the intervals between measurements were extended beyond 120 min and the data were acquired only in 10°C increments). For each temperature, measurements included data of the flux from the source and additionally of the dark signal obtained by closing the entrance window through an external shutter (this latter measurement was mostly performed to support quality checks). Both the source and dark signal measurements were performed for 2 min in 10-s intervals, which led to the collection of 12 sequential spectra each. The average of these spectra was applied in the data analysis.

In view of ensuring basic statistics, each radiometer was characterized three times. Both the potential issues due to the nonstabilization of the internal temperature of the radiometer with respect to the ambient one and the changes in the flux of the light source during the measurement sequence are addressed in the discussion section.

### b. Data reduction

Results presented in this study were obtained from the analysis of the response to the temperature change of three RAMSES ACC irradiance sensors (with serial numbers SAM-835C, SAM-82C1, and SAM-8516) and one RAMSES ARC radiance sensor (with serial number SAM-8508).

The study relies on measurements $S(\lambda_n, T)$ performed at different ambient temperature $T$ for the spectral bands $\lambda_n$ corresponding to the $n$th element of the photodetector array of each radiometer. The removal of the dark signal (i.e., the signal measured in the absence of incident light, mostly due to the photodetector dark current) was performed in agreement with documented methods (TriOS 2017; Talone et al. 2016). Specifically, the dark signal resulting from both an estimated background contribution and an additional residual noise were quantified and removed from the measured raw data $I(\lambda_n, T)$ as follows.

Raw data $I(\lambda_n, T)$ from each element of the photodetector array were normalized to the maximum counts range, 65535, as

$$M(\lambda_n, T) = I(\lambda_n, T)/65535. \quad (1)$$

The value of $M(\lambda_n, T)$ was then corrected for the background contribution as a function of the integration time $t$ according to

$$C(\lambda_n, T) = M(\lambda_n, T) - [B_0(\lambda_n) + tI_0]B_1(\lambda_n)]. \quad (2)$$

where $t_0$ is the maximum integration time (i.e., 8912 ms) and $B_0(\lambda_n)$ and $B_1(\lambda_n)$ are device-specific coefficients delivered by the spectrometer manufacturer to determine the background contribution to the dark signal. [i.e., $B_0(\lambda_n) + tI_0B_1(\lambda_n)$].

The actual measurement of the source $S(\lambda_n, T)$ at ambient temperature $T$ was then obtained from $C(\lambda_n, T)$ corrected for any residual radiometer noise $D_0(T)$ and normalized with respect to $t$ and the maximum counts range, according to

$$S(\lambda_n, T) = C(\lambda_n, T)\left(\frac{t_0}{t}\right)65535. \quad (3)$$

The term $D_0(T)$ is the average of the values of $C$, determined at $T$ and $t$ with Eq. (2) from the 18 occulted elements of the detector array located just after the near-infrared spectral region and excluded from light detection by a black sheet. Assuming that any residual noise not accounted for by the background contribution is identical for all the elements of the photodetector array, the term $D_0(T)$ allows for removing any residual noise contribution without requiring any a priori knowledge of the operating temperature of the radiometer.

Last, it is mentioned that any perturbing effect due to nonlinearity of the photodetector response was minimized by properly choosing $t$ and the distance between the tank and the integrating sphere. Specifically, data were collected, ensuring that the highest values of each spectrum did not fall in the upper range of counts (tentatively above $5 \times 10^4$), which is more affected by nonlinearity (Pacheco-Labrador and Martín 2015; Hamamatsu 2016).

### 3. Correction for the response to temperature

The response to the temperature of radiometers can be defined through the percent difference $\varepsilon$ between values of $S(\lambda_n, T)$ determined at ambient temperature $T$ and values of $S(\lambda_n, T_0)$ obtained at the reference temperature $T_0$ (here set to 20°C, which corresponds to the temperature at which the radiometers are commonly calibrated):

$$\varepsilon = 100 \frac{S(\lambda_n, T) - S(\lambda_n, T_0)}{S(\lambda_n, T_0)}. \quad (4)$$
Correction terms to compensate for the temperature dependence are then provided by the ratio

$$ R(\lambda_n, T, T_0) = S(\lambda_n, T)/S(\lambda_n, T_0). \quad (5) $$

The temperature coefficient $c(\lambda_n)$ of the radiometer [(°C)$^{-1}$] can be determined from the fit of $R(\lambda_n, T, T_0)$ as a function of the temperature difference $\Delta T = T - T_0$ for each $\lambda_n$ in the 400–800-nm spectral interval assuming a linear dependence with temperature of the radiometer response:

$$ R(\lambda_n, T, T_0) = 1 + c(\lambda_n) \times \Delta T. \quad (6) $$

The 400–800-nm spectral range, reduced with respect to RAMSES features, satisfies most ocean color field applications and excludes from the analysis those spectral regions affected by the low photodetector sensitivity (i.e., below 400 nm) or those commonly characterized by negligible values of the water-leaving radiance (i.e., the near-infrared).

In view of accounting for multiple characterizations, the average $\overline{R}(\lambda_n, T, T_0)$ of the values $R(\lambda_n, T, T_0)$ was used to determine the mean $\overline{c}(\lambda_n)$ for each individual radiometer. Results from the characterization of SAM-8508 are illustrated in Fig. 2.

Deviation from linearity of $\varepsilon$ appearing in Fig. 2a is likely due to the nonlinearity of the response to temperature or the nonequilibrium between ambient and internal-radiometer temperatures during the measurement sequence. Perturbing effects due to moisture on the external optics of the radiometer or on the inner surface of the optical window of the TC-Tank are excluded because the ambient temperature was always appreciably higher than the dewpoint temperature during measurement sequences.

Values of $\overline{c}(\lambda_n)$ determined for the irradiance sensor SAM-8508 are presented in Fig. 2b. The error bars on the y axis, which exhibit values generally lower than $0.01 \times 10^{-2}$ (°C)$^{-1}$, indicate the standard deviation of the $c(\lambda_n)$ values.

In agreement with expectations, the values of $\varepsilon$ displayed in Fig. 2a indicate that the spectral temperature dependence increases with wavelength, with the maximum values at 800 nm varying from approximately $-3\%$ at 10°C to $+7\%$ at 40°C. Notable is also the small-scale spectral variability characterizing $\overline{c}(\lambda_n)$ (see Fig. 2b). When considering the constancy of $\sigma$ across the spectrum, the former deviations exhibiting features extending over a few tens of nanometers appear to systematically affect each independent determination of $c(\lambda_n)$. This consideration suggests that the observed small-scale spectral variability of $c(\lambda_n)$ is likely related to the spectrometer performance rather than to measurement artifacts.

### 4. Discussion

The discussion focuses on the definition of a correction function minimizing the effects of the temperature response for RAMSES hyperspectral radiometers. Additionally, considering the temperature dependence of the dark signal in silicon photodetectors, the effectiveness of dark signal corrections for the specific radiometers is verified. Other elements discussed are the stability of the light source with time, and the assumption of thermal equilibrium between the internal-radiometer and ambient temperatures during measurements. Finally, in view of addressing differences in temperature response across radiometers built on different technology, the temperature coefficients of a series of multispectral radiometers is also investigated. Last, the impact of temperature coefficients on in situ ocean color radiometric measurements is discussed.
a. Class representativity of temperature coefficients for RAMSES radiometers

Figure 3a shows the values of $\tau(\lambda_n)$ determined for the four RAMSES considered in this study. The similar values of $\tau(\lambda_n)$ suggest that mean spectral temperature coefficients could be confidently proposed for RAMSES radiometers. To this end, Fig. 3 provides the values of $c^*(\lambda)$ obtained by fitting the average of $\tau(\lambda_n)$ from the various radiometers with

$$c^*(\lambda_n) = k_0 \left\{ 1 - \sum_{i=1}^{4} [k_i(\lambda_n - 400)]^4 \right\}.$$  \hspace{1cm} (7)

The standard deviation of the various $\tau(\lambda_n)$ (see the right scale in Fig. 3a) exhibits values generally within $0.03 \times 10^{-2} \, (^\circ C)^{-1}$. These latter values are an index of the uncertainty associated with the mean temperature coefficients $c^*(\lambda_n)$ computable for the sample RAMSES radiometers using Eq. (7) with the values of $k_0$ and $k_i$ (for $i=1-4$) given in Fig. 3a.

The average $\mu(\varepsilon)$ of the percent differences $\varepsilon$ between actual corrections $R(\lambda_n, T, T_0)$ determined for the various radiometers and those computed with $c^*(\lambda_n)$ are displayed in Fig. 3b. The values of $\mu(\varepsilon)$ vary between +0.1% and -0.3% in the 10°-20°C range and between +0.3% and -0.5% in the 25°-40°C interval. The increasing values with temperature are likely explained by a deviation from linearity of the radiometer response with ambient temperature.

Graphs in Fig. 3a show the statistical equivalence of $\tau(\lambda_n)$ determined for irradiance (i.e., SAM-835C, SAM-82C1, and SAM-8516) and radiance (i.e., SAM-8508) units. This finding suggests that the different optics of irradiance and radiance units do not appreciably affect the temperature coefficients of RAMSES radiometers.

Interestingly, the spectral discontinuities at the scale of tens of nanometers already observed in Fig. 2 for $\tau(\lambda_n)$ from SAM-8508 exhibit appreciable differences from unit to unit in Fig. 3a. This finding indicates that the observed small-scale variabilities are instrument specific and likely due to the responsivity nonuniformity of the photodetector array.

It should be also noted that the equivalence of $c^*(\lambda_n)$ with typical temperature coefficients of the S3904 series of photodetector arrays (Hamamatsu 2016) provides confidence in the results summarized in Fig. 3. This equivalence also suggests a small or negligible contribution of both optics and mechanical components to temperature coefficients of RAMSES radiometers.

b. Effectiveness of the dark signal correction

In the absence of any temperature stabilization, radiometers may exhibit large variations in the dark signal in addition to changes in response with temperature. The dark signal is an additive term that can be quantified and removed with supplementary measurements performed with the entrance optics closed by a shutter. In the case of RAMSES radiometers, as already detailed in section 2, the dark signal is computationally removed on a measurement-by-measurement basis accounting for the integration time, by first estimating the typical background for each element of the array through Eq. (2) and successively cancelling any residual noise contribution across all elements using the average counts from the 18 occulted elements of the photodetector array. The accuracy of such a correction process is important for any application devoted to delivering accurate measurements and is definitively critical in this study, aiming to produce correction functions for temperature response.
Figure 4a illustrates the dynamic of the dark signal for SAM-82C1 as measured with an integration time of 4096 ms. Values in digital counts vary from $10^3$ at an ambient temperature of approximately 2°C to $10^4$ at 40°C. Data in Fig. 4b show the difference between values of the dark signal determined from the occulted elements and the alternative dark values determined on an element-by-element basis with the entrance optics closed. (c) DN values refer to the dark signal as determined for SAM-8516 with different integration times from the occulted elements (i.e., computed) and those determined on an element-by-element basis with the entrance optics closed (i.e., measured). (d) DN values show the difference between the spectral values of the dark signal (i.e., computed and measured) presented in (c).

Figure 4a indicates the dynamic of the dark signal for SAM-82C1 as measured with an integration time of 4096 ms. Values in digital counts vary from $10^3$ at an ambient temperature of approximately 2°C to $10^4$ at 40°C. Data in Fig. 4b show the difference between values of the dark signal determined from the occulted elements and the alternative dark values determined on an element-by-element basis by closing the entrance optics with a shutter. Results confirm that the two-step correction procedure applied for the removal of the background signal and the residual noise is effective across the whole range of wavelengths and temperatures considered. Specifically, differences between the two signal determinations are generally within ±10 DN up to 30°C, but they may increase up to several tens of digital counts close to 40°C.

Consistent results were obtained with dark signals measured using different integration times. Specifically, for data collected at 20°C and integration times in the range of 16–8192 ms, Fig. 4c shows values of the dark signal determined through the application of the two-step correction procedure and those actually measured by closing the entrance optics with a shutter. The differences between the two determinations are displayed in Fig. 4d. Both Figs. 4b and 4d indicate some element-by-element difference with values more pronounced at the highest temperatures. Still, these differences are not significant when considering that the digital counts related to the source are generally higher than $10^4$.

c. Performance of the light source during measurement sequences

The characterization of temperature coefficients requires that the light source is stable over the full measurement sequence (approximately 6 h to cover
Because of the lack of any stability monitoring of the integrating sphere, an assessment of the overall stability of the system was performed by measuring the flux from the sphere using a RAMSES operating in the tank with $T = 20\, ^\circ\text{C}$ at 30-min intervals during 6 h. Results obtained with maximum variations of $\pm 0.2\, ^\circ\text{C}$ of the ambient temperature in the tank, indicated changes up to $\pm 0.2\%$ of $c$, corresponding to variations of approximately $0.01 \times 10^{-2} \, (\text{C})^{-1}$ of $c(\lambda_n)$ likely explained by changes with time of the source flux.

An additional assessment was made by comparing values of $c(\lambda_n)$ obtained from independent measurement sequences relying on the integrating sphere and, alternatively, on a seasoned 1000-W FEL lamp powered with feedback current control. Results indicate differences between $c(\lambda_n)$, independently determined with the lamp and the integrating sphere, varying from $0.02 \times 10^{-2} \, (\text{C})^{-1}$ at 400 nm to $0.01 \times 10^{-2} \, (\text{C})^{-1}$ at 800 nm.

Overall, the former analyses indicate possible effects of the light source instability close to the $0.01 \times 10^{-2} \, (\text{C})^{-1}$ value of the standard deviation given in Fig. 2b for multiple characterizations performed with the sphere, and thus not significantly impacting characterizations.

d. Thermal equilibrium of radiometer at the target ambient temperature $T$

The lack of information on the internal temperature of RAMSES radiometers is definitely a source of uncertainty affecting the determination of temperature coefficients. With respect to this, conditions essential for the applicability of the proposed method and, consequently, of Eq. (6) are as follows:

(i) Linear variation of the differences between internal-instrument and ambient temperatures in the considered range of values, assuming that temperatures are homogeneous inside both the TC-Tank and the radiometer during measurements. The assumption on linearity is likely challenged by the heat produced by the radiometer electronics with effects more pronounced below $10\degree -15\degree \text{C}$.

(ii) Thermal equilibrium of the radiometer at each ambient temperature $T$ at which measurements are performed.

Within the precision of measurements, the assumption on the thermal equilibrium of the radiometer in the TC-Tank is confirmed by the agreement between results obtained from the application of the proposed method and results from characterizations performed by increasing from approximately 60 to 120 min the interval between successive measurements.

With reference to SAM-8508, Fig. 5a shows the differences $d(\varepsilon)$ between the values of $\varepsilon$ determined from $S(\lambda_n, T)$, applying the two alternative measurement schemes only differing by the time interval between successive measurements. Noteworthy, values of $\varepsilon(\lambda_n)$ (obtained from measurements performed in 60-min intervals) and $c(\lambda_n)$ (obtained with 120-min intervals) displayed in Fig. 5b exhibit differences within the standard deviation of $\varepsilon(\lambda_n)$. The larger deviations in the 400–420-nm interval (see the black lines in Fig. 5a and the red line at 400 nm in Fig. 5b) are due to the noise affecting the single characterization performed with the extended time interval between measurements.

e. Temperature coefficients for a series of multispectral radiometers

In view of further investigating the temperature response of optical radiometers commonly used by the ocean color community, radiometers from the OCR-500 series manufactured by Satlantic Inc. (Halifax, Canada) were also characterized. Unlike RAMSES, OCR-500
radiometers are multispectral devices built on Hamamatsu S2386 silicon photodiodes coupled to interference filters. Specifically, four OCR-507 radiometers (i.e., serial numbers Ed049, Ed144, Es045, and Es146) with a spectral bandwidth of 10 nm centered at 412, 443, 490, 510, 555, 670, and 683 nm were characterized. OCR-507 radiometers are equipped with an internal thermistor. Because of this, their temperature characterizations were performed using the internal-instrument temperature $T$. In the case of the OCR-507 radiometers, the values of $S(\lambda_n, T)$ for each temperature $T$ and spectral band $\lambda_n$ were computed accounting for the actual dark signal measured with the entrance optics closed by a shutter.

Figure 6a shows the values of $\varepsilon$ determined as a function of $T$ for the various bands of Ed049. The results exhibit $\varepsilon$ values generally within ±0.5% at the extremes of the temperature interval for the various bands, with 412 nm excluded. This latter shows values varying from +1.5% at +10°C to almost −3% at +50°C. The related values of $\tau(\lambda_n)$ for multiple characterizations are shown in Fig. 6b.

The abovementioned results for Ed049 cannot be solely explained by the temperature coefficient of the S2386 silicon photodiodes. In fact, the temperature coefficient slowly increases toward the blue wavelengths with typical values of approximately $-0.05 \times 10^{-2}$ (°C)$^{-1}$ at 400 nm (Hamamatsu 2006). It is then plausible that the temperature response at 412 nm of the OCR-507 is also affected by changes with the temperature of the spectral characteristics of the interference filter. Equivalent temperature responses at 412 nm were also determined for all radiometers, even though a previous characterization performed during 2012 indicated lower values for Es146 (see Fig. 7a). This change in performance is explained by

![Figure 6a](image1.png)

**FIG. 6.** (a) Percent difference $\varepsilon$ between $S(\lambda_n, T)$ determined at $T$ and $S(\lambda_n, T_0)$ obtained at $T_0 = 30°C$, and (b) values of $\tau(\lambda_n)$, all obtained for Ed049. Error bars on the y axis of (b) indicate the standard deviation for independent determinations of $c(\lambda_n)$.

![Figure 7a](image2.png)

**FIG. 7.** Differences $d(\varepsilon)$ between values of $\varepsilon$ determined in 2012 and 2017 from $S(\lambda_n, T)$ at $T$ and $S(\lambda_n, T_0)$ obtained at $T_0 = 30°C$ for (a) Es146 and (b) Es045.
the replacement of the 412-nm detector (i.e., photodiode and filter) between the two characterizations.

In addition to the band at 412 nm, further dissimilarities are also observed at 555 nm for both Es045 (see Fig. 7b) and Ed144 (not shown). These dissimilarities are probably related to the degradation of interference filters, even though they were undetectable through regular absolute radiometric calibrations. This finding is supported by a characterization performed for Ed144 during 2012. At that time, the temperature coefficient determined for the 555-nm band was in agreement with results obtained for Ed049 and Es146.

f. Implications for in situ ocean color radiometry

Changes in temperature sensitivity may affect measurements in the diverse spectral regions differently. Coincidentally, the radiance emerging from natural waters is generally negligible in the near-infrared, where mostly used silicon photodiodes exhibit a higher value of the temperature coefficient. Still, considering the instruments analyzed in this study, changes in temperature of 20°C with respect to the reference temperature at which the radiometers are calibrated may lead to changes in spectral response on the order of $-0.8 \pm 0.6\%$ at 400 nm for RAMSES radiometers, decreasing to approximately $\pm0.6\%$ at 470 nm, and then increasing to $+6.6 \pm 0.6\%$ at 700 nm. In the case of OCR-507 radiometers, when not affected by aging effects of interference filters, variations in response induced by changes in temperature of 20°C are expected to be within $\pm 0.4\%$ for the bands in the 443–683-nm spectral interval and $-2.4 \pm 0.3\%$ at the 412-nm band. Still, it must be considered that aging of filters may introduce much larger changes.

Last, we are reminded that accurate determinations of temperature effects require knowledge of the working temperature of the radiometer via its direct reading or, alternatively, assuming known relations with ambient temperature. For in-air radiometers not equipped with an internal thermistor, however, the air temperature may not conveniently represent the working temperature of radiometers when these are exposed to direct sunlight. In the alternative case of in-water radiometers operated in the presence of vertical temperature stratifications, it is also unlikely that the thermal equilibrium can be constantly reached during profiling.

The previous general considerations suggest objective difficulties in the implementation of accurate corrections for temperature response without information on the internal-instrument temperature and away from the condition of thermal equilibrium. In this respect, various works (Kuusk 2011; Pacheco-Labrador and Martín 2015) showed well-defined exponential relationships between dark signal and temperature for MMS-1 spectrometers with high integration times. This finding is further confirmed in Fig. 8a for the dark signal determined from the occulted elements of the detector arrays for two RAMSES radiometers (i.e., SAM-8508 and SAM-8516). These results may suggest (see Ghezehegn et al. 2015) that the working temperature of RAMSES radiometers can be confidently related to the dark signal determined from the occulted elements. Nevertheless, it should be noted that this solution is mostly restricted to temperatures higher than approximately 15°C, for which changes in the dark signal exhibit significant dependence with temperature variations.

Practical application of such a correction approach, however, implies dark signal measurements performed with a high integration time after closing the entrance optics of the radiometer through an external shutter. The alternative collection of the dark signal from the
occulted elements without closing the entrance optics could produce blooming, that is, an overflow of charge from the saturated elements of the detector array into the nearby ones leading to an overestimate of the dark signal. This is illustrated in Fig. 8b through the digital counts of the occulted elements of SAM-8516 determined with the entrance optics closed or illuminated by the integrating sphere. In the specific case, data indicate an increase of blooming effects with integration time when saturation occurs (i.e., for $t > 256$ ms).

5. Conclusions

The response to temperature change of four RAMSES hyperspectral radiometers built on silicon photodetector arrays was investigated in the 400–800-nm spectral interval. Results determined on the basis of the external radiometer temperature (i.e., ambient temperature) in the $10^\circ$–$40^\circ$C range, indicate that the precision of individual characterizations is generally better than $0.01 \times 10^{-2}$ $(^\circ$C)$^{-1}$ as quantified by the standard deviation of multiple determinations of the temperature response for each individual radiometer. Average temperature coefficients of the various sample radiometers indicate spectral values varying from $(-0.04 \pm 0.03) \times 10^{-2}$ $(^\circ$C)$^{-1}$ at 400 nm to $(+0.33 \pm 0.03) \times 10^{-2}$ $(^\circ$C)$^{-1}$ at 800 nm, which are largely explained by the typical temperature response of the photodetector array constituting the core of the radiometer.

Overall, the results suggest the possibility of applying temperature corrections for the specific class of hyperspectral radiometers with an estimated uncertainty of approximately $0.03 \times 10^{-2}$ $(^\circ$C)$^{-1}$ given by the standard deviation of the temperature coefficients of the various radiometers across the considered spectral and temperature ranges.

The operational application of temperature coefficients to RAMSES radiometers, still, requires knowledge of the ambient temperature. Even though in field conditions the air temperature is likely the best guess for ambient temperature, direct sunlight may largely affect the internal-radiometer temperature. A practical solution, mostly applicable for ambient temperatures higher than $15^\circ$C, is given by relationships linking the temperature to the dark signal determined with high values of the integration time through an external shutter to prevent saturation and thus to avoid blooming effects in the occulted elements of the photodetector array. Still, it is suggested that in the future thermistors are always integrated into optical radiometers.

In addition to RAMSES, sample multispectral radiometers from the OCR-507 series were characterized. These radiometers have seven bands 10 nm wide in the 400–700-nm region and are equipped with an internal thermistor. This additional investigation was mostly suggested from interest in evaluating the temperature response of radiometers built on different technology (i.e., interference filters coupled to photodiode detectors). In this case results indicate typical temperature sensitivities more relevant in the blue spectral region at 412 nm with a temperature coefficient of $(-0.12 \pm 0.015) \times 10^{-2}$ $(^\circ$C)$^{-1}$ and within $\pm 0.02 \times 10^{-2}$ $(^\circ$C)$^{-1}$ for all the other bands. However, exceptions are observed likely due to a significant temperature response of filters at 412 nm and filter degradation at 555 nm. These radiometer-to-radiometer differences indicate the possibility of introducing spectral inconsistencies in the measured spectra as a function of temperature when temperature coefficients are not regularly determined or verified.

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