Non-linear response of a class of hyper-spectral radiometers

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Abstract
The non-linear response of RAMSES hyperspectral radiometers was characterized in the 450 nm–800 nm spectral region. Results indicate inverse proportionality of the non-linearity with the output counts. The departure from linearity is generally within ±1.5% with maxima at the longest wavelengths. Notably, the consistency of results across different instruments suggests the possibility of applying corrections to the entire class of RAMSES radiometers with residuals generally lower than 0.3%. Finally, an analysis based on field measurements from different water types indicates that non-linearity can contribute up to 1.5% to the relative uncertainties affecting spectra of remote sensing reflectance.

Keywords: non-linearity, hyperspectral radiometry, ocean colour

(Some figures may appear in colour only in the online journal)

1. Introduction
Hyperspectral optical radiometers are widely used in Earth observation applications to measure in situ spectral remote sensing reflectance of natural surfaces. Underlying assumption is their linear response, or at least the capability to correct for their non-linearity. In fact, even though often neglected, photodetectors are intrinsically non-linear devices [1, 2].

Due to the different spectral signatures of calibration and natural targets, and additionally because of the high variability of these latter, non-linearity can produce unwanted features in radiometric measurements with a consequent increase of uncertainties. For this reason, best practice suggests to characterize the response of hyperspectral radiometers over their entire dynamic and spectral ranges before field use.

Radiometers non-linearity is often expressed as a function of the output counts [3]. However, besides counts, also the readout time (i.e. the time needed to read the detector array and preset the successive measurement) has been indicated as an additional source of non-linearity [4].

Focusing on a class of hyperspectral radiometers extensively applied to support satellite ocean color investigations, this work addresses their non-linearity through the analysis of the effects of both output counts and integration time.

2. Materials and methods
2.1. Radiometers
All radiometers included in the following analyses are RAMSES sensors manufactured by TriOS Mess-und Datentechnik GmbH (Rastede, Germany). Namely, four RAMSES-ACC irradiance units with serial numbers SAM-82C1, SAM-835C, SAM-84C0, and SAM-8516 were used for laboratory characterizations. Additionally, together with the aforementioned SAM-835C, three RAMSES-ARC radiance units with serial numbers SAM-8346, SAM-8313, and SAM-8508, were applied for the collection of field measurements. RAMSES-ACC and RAMSES-ARC are based on the same design and share most of their components, except the foreoptics. Specifically, RAMSES-ACC radiometers rely on a cosine collector of 3.5 mm diameter while RAMSES-ARC have a condenser lens defining a full-angle field-of-view of approximately 7 degrees. In both cases, the foreoptics module is coupled to a fiber bundle that feeds a ZEISS (Oberkochen, Germany) Monolithic Miniature Spectrometer (MMS-1) built on the Hamamatsu (Ichino-cho, Japan) S3904 256-channel NMOS array. The integration time can be set between 4 ms...
and 8192 ns to optimize the output range for very different targets and illumination conditions. Finally, the spectral resolution is approximately 10 nm with average spectral sampling of 3.3 nm in the 320 nm–950 nm interval.

### 2.2. Laboratory measurements

The characterization of the non-linearity of radiometers may conveniently rely on a point source and the application of the inverse-square law [3]. This allows producing measurements with different flux by simply changing the distance between source and entrance optics of the radiometer. In agreement with such a general principle, laboratory measurements for non-linearity characterization were performed using a lamp installed on a 2 m calibration bench. Alignment of the various system components (i.e., rail, source, radiometer holder) was obtained with a laser. The positioning of radiometers was performed manually with an expected uncertainty lower than 0.5 mm on the distance between lamp posts and front plate of the radiometer. Such an uncertainty is expected to affect the non-linearity characterization by less than 0.1% [5].

The sources applied to produce the measurements required, were three seasoned FEL 1000 W lamps with filaments of different size: H96531 from Hoffmann Engineering (Stamford, USA); GO1373 from Gooch & Housego (Orlando, USA); and EGG238 from EG&G (Gaithersburg, USA). Horizontal and vertical dimensions of the lamp filaments are 8 mm and 20 mm, 10 mm and 21 mm, and 10 mm and 20 mm for H96531, GO1373, and EGG238, respectively. All the results included in this study were obtained relying on H96531, but were confirmed from the application of GO1373 and EGG238.

For each radiometer-lamp pair, two independent types of measurement were performed: the first directed to quantify the exact position of the sensor receiving and source radiating planes, and the second one to characterize the non-linearity of the radiometer. Additional measurements were performed to evaluate the impact of the integration time as well as that of the non-ideal cosine response of the collector on non-linearity analysis.

A common measurement protocol was adopted for all laboratory characterizations. Specifically, the environmental background was measured for each irradiance determination by shading the cosine collector with an occluder positioned at distances from the radiometer allowing to cast a shadow of equivalent dimension on its front plate regardless of the radiometer-lamp distance. For all the measurements, including both those performed to determine the light flux and the background signal, the dark signal was computed in agreement with a verified scheme [6] and removed. Afterwards, for each flux measurement the corresponding background values were subtracted and the resulting output counts applied in the following analyses. Finally, dark measurements were also performed at the beginning and at the end of each session with the radiometer aperture closed, and, as a quality check, compared to the corresponding computed ones [7].

### 2.3. Characterization of the non-linearity of RAMSES-ACC radiometers

As already introduced in section 2.2, the characterization of the non-linearity of radiometers was conveniently performed using FEL lamps and applying the inverse-square law. In the ideal case of (i) a non-attenuating transmission medium, (ii) a point source of spectral radiant intensity $I$, and (iii) a point detector looking at the source [8], the radiometer output in counts is expressed by:

$$DN(\lambda, D, \tau) = \frac{I(\lambda)}{D^2} \Re(\lambda) \tau,$$

where $\Re(\lambda)$ is the radiometer responsivity as a function of wavelength $\lambda$, $D$ the distance between source and entrance optics, and $\tau$ the integration time. For laboratory measurements performed with lamps, the radiant intensity $I(\lambda)$ is determined by the lamp calibration irradiance value $E_C(\lambda)$ normalized to the distance $D_c$ applied for its absolute calibration, i.e., $I(\lambda) = E_C(\lambda)D_c^2$.

It is emphasized that the inverse-square law holds exactly for a point detector and a point source. As such, its inaccuracy increases with the size of source and entrance optics as well as with a reduction of the distance between them. In view of dealing with actual sources and radiometers, correction models were proposed for the inverse-square law to account for the actual dimensions of the aperture of the entrance optics and of sources such as FEL lamps. In the specific case of an irradiance sensor and of a FEL lamp [9], (1) can be rewritten as:

$$DN(\lambda, D, \tau) = \frac{I(\lambda)}{D^2 + r_s^2 + r_t^2} \Re(\lambda) \tau,$$

with $r_s$ and $r_t$ indicating the equivalent source and radiometer aperture radii given by

$$r_s = 0.5 \sqrt{\frac{m + p + 2}{6} \chi_0^2 + \frac{m + q + 2}{6} \chi_0^2},$$

and

$$r_t = 0.5 \frac{m + q + 2}{2} + 2,$$

where $\chi_0$ and $\chi_0$ are the equivalent horizontal and vertical dimensions of the source, and $r_0$ is the radius of the aperture. For cosine collectors (i.e., collectors used for irradiance measurements that exhibit angular response varying with the cosine of the incidence angle), the parameter $m$ is set to 1. The parameters $p$ and $q$, which account for the angular distribution of the source flux, are set to 0 and 5 for FEL lamps.

Further, the distance $D$ needs to account for potential offsets affecting the exact position of the reference planes of both lamp and cosine collector [9, 10]. This is done by defining $D = d + \delta_1 + \delta_2$, with $d$ the distance between the front plate of the radiometer and the lamp posts, $\delta_1$ the distance between the front plate of the radiometer and its receiving reference plane, and $\delta_2$ the distance between the posts of the lamp and its radiating reference plane.
Finally, a comprehensive model for a radiometer-source system implies the capability to account for the non-linearity of the radiometer itself. This can be done by applying to the radiometer spectral responsivity a correction factor $\varepsilon$ function of the output counts $DN(\lambda, d, \tau)$, i.e. $R(\lambda) = R_0(\lambda) \{1 + \varepsilon[DN(\lambda, d, \tau)]\}$ with $R_0(\lambda)$ the ideal spectral responsivity of a sensor exhibiting linear response to the incident flux. Consequently, by indicating with $DN_L(\lambda, d, \tau)$ the value of $DN(\lambda, d, \tau)$ corrected for non-linearity, (2) becomes

$$DN_L(\lambda, d, \tau) = \frac{I(\lambda)}{(d + \delta_s + \delta_l) + 1} \times R_0(\lambda) \{1 + \varepsilon[DN(\lambda, d, \tau)]\} \tau,$$

whose parameters $\delta_s$, $\delta_l$, and $\varepsilon[DN(\lambda, d, \tau)]$ can be estimated by varying the nominal distance $d$ and the integration time $\tau$. It is noted that (5) does not explicitly account for the dependence of non-linearity on $\tau$.

### 2.3.1 Determination of the lamp and collector distance offsets

For each radiometer-lamp pair, the sum of the offsets affecting both the collector and the lamp reference planes (i.e. $\delta = \delta_s + \delta_l$) likely varying with $\lambda$, was determined with successive measurements identified by the index $i$ and performed, as specified in table 1, with integration times $\tau_i$ and distances $d_i$.

| $i$ | $d_i$/mm | $\tau_i$ | $DN_i(\lambda_0, d_i, \tau_i)/10^3$ counts |
|-----|---------|---------|-----------------------------------|
| 1   | 500     | $\tau_0$ | 30 $\pm$ 3                        |
| 2   | 710     | $2\tau_0$ | 30 $\pm$ 3                       |
| 3   | 1000    | $4\tau_0$ | 30 $\pm$ 3                       |
| 4   | 1420    | $8\tau_0$ | 30 $\pm$ 3                       |

Table 1. Parameters applied for the determination of the distance offsets $\delta(\lambda)$. Measurement series, distances, integration times, and the corresponding output counts at $\lambda_0 = 600$ nm, are indicated by $i$, $d_i$, $\tau_i$, and $DN_i(\lambda_0, d_i, \tau_i)$, respectively.

Figure 1. Average output counts $DN(\lambda, d, \tau)$ applied for the determination of the non-linearity of SAM-8516. The various measurement series (see table 2) are indicated by the index $i$ and identified by different colors.

$$DN_i(\lambda, d_i, \tau_i)/[\{d_i + \delta(\lambda)\}^2 + r_i^2 + r_i^2]/\tau_i$$

Values of $\delta(\lambda)$ were determined both from the comparison of individual measurements performed at distances $d_i$ with the reference values obtained at $d_1$, and alternatively from the simultaneous application of all measurements by minimizing the function:

$$\chi^2(\lambda) = \sum_i \{DN_i(\lambda, d_i, \tau_i)/\{d_i + \delta(\lambda)\} + r_i^2 + r_i^2\}/\tau_i$$

As a result of the small spectral dependence of $\delta(\lambda)$, a single $\delta$ specific of each radiometer-lamp pair was determined by averaging the available spectral values $\delta(\lambda)$.

### 2.3.2 Determination of the non-linearity factors

Relying on the distance offset $\delta$ determined in section 2.3.1, non-linearity factors $\varepsilon[DN(\lambda, d_i, \tau_i)]$ were estimated from series of measurements performed at different distances $d_i$ with constant integration time $\tau_0$ (see figure 1). The parameters defining the measurement conditions for each radiometer-lamp pair are listed in table 2.

Specifically, for each output $DN_i(\lambda, d_i, \tau_0)$, the non-linearity factors were determined as:

$$DN_i(\lambda, d_i, \tau_0)/[\{d_i + \delta(\lambda)\}^2 + r_i^2 + r_i^2] = 1,$$

where $DN_i(\lambda, d_i, \tau_0)$ indicates the radiometer output in a narrow range of reference counts (i.e. $30 \pm 3 \times 10^3$) implying $\varepsilon[DN(\lambda, d_i, \tau_0)] \geq 0$.

Non-linearity factors $\varepsilon[DN(\lambda, d_i, \tau_0)]$ were modeled by imposing a linear trend according to:

$$\varepsilon[DN(\lambda, d_i, \tau_0)] = a(\lambda)[DN(\lambda, d_i, \tau_0) - 30 \times 10^3].$$

Three independent characterizations were performed for each radiometer implying the complete de-installation and
Table 2. Parameters applied for the determination of the non-linearity factors \( \varepsilon [D_{N}(\lambda, d_{i}, \tau_{0})] \). Measurement series, distances, integration times, and the corresponding output counts at \( \lambda_{0} = 600 \) nm, are indicated by \( i, d_{i}, \tau_{i} \), and \( D_{N}(\lambda_{0}, d_{i}, \tau_{i}) \), respectively.

| \( i \) | \( d_{i} \) (mm) | \( \tau_{i} \) | \( D_{N}(\lambda_{0}, d_{i}, \tau_{i}) / 10^{3} \) counts |
|-------|-----------------|-------------|-----------------------------------------------|
| 1     | 500             | \( \tau_{0} \) | \( \approx 60 \) |
| 2     | 520             | \( \tau_{0} \) | \( \approx 55 \) |
| 3     | 550             | \( \tau_{0} \) | \( \approx 50 \) |
| 4     | 570             | \( \tau_{0} \) | \( \approx 45 \) |
| 5     | 600             | \( \tau_{0} \) | \( \approx 41 \) |
| 6     | 650             | \( \tau_{0} \) | \( \approx 35 \) |
| 7     | 700             | \( \tau_{0} \) | \( \approx 30 \) |
| 8     | 770             | \( \tau_{0} \) | \( \approx 25 \) |
| 9     | 850             | \( \tau_{0} \) | \( \approx 20 \) |
| 10    | 1000            | \( \tau_{0} \) | \( \approx 15 \) |
| 11    | 1200            | \( \tau_{0} \) | \( \approx 10 \) |
| 12    | 1400            | \( \tau_{0} \) | \( \approx 8 \) |

re-installation of the measurement setup for each of them. Operational factors \( \bar{a}(\lambda) \) for each radiometer were then determined by averaging the values of \( a(\lambda) \) from the independent characterizations. By relying on \( \bar{a}(\lambda) \), the residual non-linearity still affecting the data after applying the correction, was calculated as:

\[
e[D_{N}(\lambda, d_{i}, \tau_{0})] = \varepsilon[D_{N}(\lambda, d_{i}, \tau_{0})] - \varepsilon[D_{N}(\lambda, d_{i}, \tau_{0})] = 30 \times 10^{3}.
\]

Finally, assuming that the radiometer foereoptics does not affect linearity, factors \( \bar{a}(\lambda) \) likely applicable to any RAMSES-ACC or -ARC radiometer (see section 4) were determined from the average of the \( \bar{a}(\lambda) \) values from the various RAMSES-ACC units characterized in this study.

2.3.3. Evaluation of the impact of integration time on non-linearity. The previous methods do not imply any impact of the integration time on the determination of the sensor non-linearity because of the application of a sole value (i.e. \( \tau_{0} \)).

To assess the impact of integration time on both the determination of the distance offsets and the characterization of the radiometer non-linearity, a series of specific measurements were performed with various integration times \( \tau_{i} \) at three different distances \( d_{i} \) from the source (see table 3). Measurements were corrected for the non-linearity only due to the output counts by applying the coefficients \( \bar{a}(\lambda) \) determined in agreement with the details provided in section 2.3.2, and additionally normalized with respect to \( \tau_{i} \). Specifically, by setting a reference integration time \( \tau_{0} = 256 \) ms, all radiometers were characterized with values of \( \tau_{i} \) varying in the range of 32 ms–1024 ms, likely embracing those \( \tau_{i} \) applicable for measurements over the majority of natural targets and illumination conditions.

The non-linearity only due to \( \tau_{i} \), \( \varepsilon_{\tau}[D_{N}(\lambda, d_{i}, \tau_{i})] \), was estimated as:

\[
\varepsilon_{\tau}[D_{N}(\lambda, d_{i}, \tau_{i})] = \frac{D_{N}(\lambda, d_{i}, \tau_{i}) \times \bar{a}(\lambda)[D_{N}(\lambda, d_{i}, \tau_{i}) - 30 \times 10^{3}]}{D_{N}(\lambda, d_{i}, \tau_{0}) \times \bar{a}(\lambda)[D_{N}(\lambda, d_{i}, \tau_{0}) - 30 \times 10^{3}]} - 1.
\]

This specific analysis was further extended by accounting for the readout time \( t_{r} \), which is the time required to set the reference cathode voltage of the individual elements of the detector array [11]. Considering that Hamamatsu S3904 arrays have readout time included in the integration time [12], the effective integration time during which incident photons contribute to the output current is \( \tau_{i} - t_{r} \). Assuming an exact correction for non-linearity as a function of the output counts and introducing \( \tau_{i} - t_{r} \) in (12), the non-linearity contribution due to readout time, \( \varepsilon_{\tau_{r}}(\tau_{i}, t_{r}) \), was computed from:

\[
\varepsilon_{\tau_{r}}(\tau_{i}, t_{r}) = \frac{(\tau_{i} - t_{r})/\tau_{i} - 1}{(\tau_{0} - t_{r})/\tau_{0}}.
\]

2.3.4. Determination of the impact of the non ideal cosine response of collectors on non-linearity characterizations. An ideal cosine response of the radiometer collector is implicitly assumed when setting \( m = 1 \) in (3) and (4) for the determination of \( \delta \). However, a non ideal cosine response was formerly reported for RAMSES-ACC radiometers [13]. Thus, in view of investigating its impact on the characterization of non-linearity, a series of measurements were performed with 20° tilted angle of the flux on the collector plane instead of applying the reference configuration with the collector plane normal to the flux. All the measurements listed in table 1 and a subset of those detailed in table 2 (namely \( i = 1, 7, 10, \) and 12) were repeated for the tilted configuration in view of comparing the non-linearity results with those obtained applying the reference configuration.

2.4. Quantification of the impact of non-linearity on field measurements

In situ measurements of spectral \( R_{m}(\lambda) \) from natural waters, which is a key quantity for satellite ocean color applications [14], were used to evaluate the impact of non-linearity on measurement uncertainty. \( R_{m}(\lambda) \) can be obtained by combining simultaneous radiance and irradiance measurements acquired with a specific geometry [15]. In particular, radiometric measurements were collected exploiting the capability of autonomously determining the integration time of RAMSES radiometers during ideal illumination conditions and calm sea in the Western Black Sea and the Central Mediterranean Sea in June 2016 and June 2017, respectively. A number of measurements including chlorophyll-dominated
waters, waters rich in sediment, and waters characterized by high concentrations of colored dissolved organic matter, were analyzed. Overall, measurements were performed with chlorophyll-a concentrations varying between 0.05 µg l⁻¹ and 10 µg l⁻¹ and sun zenith angles comprised between 10° and 65°. The variability of both the optical properties of water and of the illumination conditions, led to a wide range of measured spectra with values comprised between 10 × 10³ counts and 60 × 10³ counts below 600 nm, and generally lower than 30 × 10³ counts at longer wavelengths. For all measurement conditions, data were collected satisfying requirements for both above- and in-water methods [14]. Namely, coincident measurements of total downward irradiance at the sea surface \( E_d(\lambda) \), total radiance from the sea \( L_T(\lambda) \), sky radiance \( L_s(\lambda) \), and sub-surface upwelling radiance \( L_u(\lambda) \) were collected. Above- and in-water derived remote sensing reflectances, \( R_{rs}^a(\lambda) \) and \( R_{rs}^i(\lambda) \), respectively, were calculated as:

\[
R_{rs}^a(\lambda) = \frac{[L_T(\lambda) - \rho \ L_s(\lambda)]}{E_d(\lambda)},
\]

with \( \rho \) the sea surface reflectance factor [16, 17] here assumed spectrally constant and equal to 0.028, and:

\[
R_{rs}^i(\lambda) = 0.543 \frac{L_u(\lambda)}{E_d(\lambda)},
\]

where the factor 0.543 accounts for both the transmittance of the water-air interface and the change of the radiometer field-of-view due to the water refractive index. The measurement methods as well as the data reduction are detailed in [18].

Applying the assumption that the radiometer foreoptics does not affect linearity, results obtained from the characterization of the RAMSES-ACC irradiance sensors are confidently extended to the RAMSES-ARC radiance units. Thus, considering that both calibration and field measurements are affected by non-linearity and that this latter is modeled as a linear function of the output counts, when neglecting higher order contributions the impact of non-linearity \( \varepsilon[\Delta(\lambda)] \) on the individual radiometric quantities \( \Delta \) (i.e. \( E_d, L_T, L_s, \text{ or } L_u \)) is given by:

\[
\varepsilon[\Delta(\lambda)] = \bar{a}(\lambda) \left[ \Delta N_{3,F}(\lambda) - \Delta N_{3,C}(\lambda) \right],
\]

where \( \bar{a}(\lambda) \) is the non-linearity correction coefficient (see section 4) applicable to the RAMSES class of radiometers, and the subscripts \( F \) and \( C \) indicate the field and calibration counts, respectively.

Field data for the determination of \( R_{rs}^i(\lambda) \) of natural waters, were analysed as a function of the measurement method, either above- or in-water, and also accounting for the spectral features of \( R_{rs}^a(\lambda) \). In particular, three typical \( R_{rs}^a(\lambda) \) spectra exhibiting maxima at wavelengths shorter than 450 nm, around 500 nm, and longer than 550 nm, were considered. The corrected above- and in-water remote sensing reflectance values were calculated by applying the factors \( \varepsilon[\Delta(\lambda)] \) to each measurement contributing to its determination. The impact of non-linearity on \( R_{rs}^a(\lambda) \), indicated by \( \varepsilon[\Delta[\varepsilon R_{rs}^a(\lambda)] \) for the above-water measurements and by \( \varepsilon[\Delta R_{rs}^i(\lambda)] \) for the in-water ones, were obtained as the difference between uncorrected and corrected values with respect to these latter. Additionally, the corresponding non-linearity effects on \( R_{rs}^a(\lambda) \) in absolute terms, denoted as \( \Delta[\varepsilon R_{rs}^a(\lambda)] \) and \( \Delta[\varepsilon R_{rs}^i(\lambda)] \), were calculated by multiplying \( \varepsilon[\Delta[\varepsilon R_{rs}^a(\lambda)] \) and \( \varepsilon[\Delta[\varepsilon R_{rs}^i(\lambda)] \) by the corresponding \( R_{rs}^a(\lambda) \) or \( R_{rs}^i(\lambda) \).

Finally, in view of generalizing the above analysis, the relative uncertainties \( u_i[R_{rs}^a(\lambda)] \) and \( u_i[R_{rs}^i(\lambda)] \) due to non-linearity were computed as the root mean square of the corresponding \( \varepsilon[\Delta R_{rs}^a(\lambda)] \) and \( \varepsilon[\Delta R_{rs}^i(\lambda)] \) applying the entire measurement dataset assumed representative for typical classes of remote sensing reflectance spectra:

\[
u_i[R_{rs}^\lambda(\lambda)] = \left\{ \frac{1}{N} \sum_N [\Delta[\varepsilon R_{rs}^\lambda(\lambda)]^2 \right\}^{1/2},
\]

where the superscript \( \times \) indicates either the data related to in-water \( i \) or above-water \( a \) measurement methods, and \( N \) is the number of measurements pertaining to each class of spectra.

Analogously, the contributions to absolute uncertainties due to non-linearity \( u_a[R_{rs}^a(\lambda)] \) and \( u_a[R_{rs}^i(\lambda)] \) were computed as the root mean square of the \( \Delta[\varepsilon R_{rs}^a(\lambda)] \) or \( \Delta[\varepsilon R_{rs}^i(\lambda)] \) values from:

\[
u_a[R_{rs}^\lambda(\lambda)] = \left\{ \frac{1}{N} \sum_N [\Delta[\varepsilon R_{rs}^\lambda(\lambda)]^2 \right\}^{1/2}.
\]

### 3. Results

#### 3.1. Non-linearity of RAMSES radiometers

Results from the determination of \( \delta \) and \( \varepsilon[\Delta N_i(\lambda, d_i, \tau_i)] \), and also results from the analysis of the impact on non-linearity of integration time and effects induced by the non ideal cosine response of irradiance collectors, are presented hereafter.

##### 3.1.1. Lamp and collector distance offsets

The output counts collected applying SAM-8516 and H96531 together with the estimated distance offsets \( \delta(\lambda) \) are illustrated in figure 2. Due to the specific combination of spectral radiometer responsivity and lamp flux, the output rapidly increases from \( 3 \times 10^3 \) counts to approximately \( 30 \times 10^3 \) counts between 400 nm and 550 nm, while it remains almost constant at longer wavelengths. The \((30 \pm 3) \times 10^3\) count thresholds shown by the dotted lines in figure 2(a) identify the spectral regions used to calculate \( \delta(\lambda) \), while the dashed lines indicate the absolute differences between \( DN_i(\lambda, d_i, \tau_i) \) and \( DN_i(\lambda, d_1, \tau_0) \). For the particular case presented in figure 2, the values of \( \delta(\lambda) \) were obtained for each spectral channel between 540 nm and 790 nm. These are displayed in figure 2(b) with solid and dashed lines indicating results obtained by either direct comparisons of \( DN_i(\lambda, d_i, \tau_i) \) with \( DN_i(\lambda, d_1, \tau_0) \), or alternatively the minimization of the function \( \chi^2(\lambda) \).

The different cases exhibit similar offset values. The largest difference, obtained applying the output counts measured at \( d_2 \) and \( d_1 \), was approximately 0.5 mm, still comparable with the positioning uncertainty. Finally, the high spectral uniformity of the retrieved \( \delta(\lambda) \) supports the robustness of the methodology applied.

When considering all the radiometer-lamp pairs, the spectrally averaged values of \( \delta \) varied between 0.4 mm and 3.1 mm.
3.1.2. Non-linearity factors. The non-linearity factors $\varepsilon_i(DN_i(\lambda, d_i, \tau_0))$ computed from (9), are displayed in figure 3. Due to the combination of low flux from the source and low responsivity of the sensor, the values of $\varepsilon_i(DN_i(\lambda, d_i, \tau_0))$ were not determined below 480 nm where $DN_i(\lambda, d_i, \tau_0)$ never reached the reference values $DN_R(\lambda, d_R, \tau_0) = (30 \pm 3) \times 10^3$. The non-linearity factors indicated an almost linear dependence with the output counts, more pronounced at the longest wavelengths, with values typically varying within $\pm 1.5\%$. The average values of $a(\lambda)$ from three independent determinations, indicated as $\bar{a}(\lambda)$, are displayed in figure 4 for SAM-8516.

Consistently with data shown in figure 3, the average slope $\bar{a}(\lambda)$ of the non-linearity factors is always negative with values increasing with $\lambda$. Specifically, it varies from $-0.2 \times 10^{-6}$ counts$^{-1}$ at 480 nm to $-0.6 \times 10^{-6}$ counts$^{-1}$ at 800 nm. Similarly, also the standard deviation of $a(\lambda)$ indicated by the errorbars in figure 4, increases with wavelength and reaches the maximum of $0.05 \times 10^{-6}$ counts$^{-1}$ at 800 nm.

Non-linearity residuals $\varepsilon_i(DN_i(\lambda, d_i, \tau_0))$ displayed in figure 5 for SAM-8516, indicate precision of corrections generally within $\pm 0.15\%$ across the whole output range. As an additional test, a 3rd-order polynomial was applied instead of the linear fit. Values of $\varepsilon_i(DN_i(\lambda, d_i, \tau_0))$ comprised within $\pm 0.07\%$ were obtained in this case. However, to minimize the possibility of overfitting, and thus of introducing artifacts in the corrected output counts, the 1st-order regression was preferred in the successive analyses.

3.1.3. Impact of integration time on non-linearity. As reported in [4, 19], linearity may exhibit dependence with integration time. Figure 6 shows that for RAMSES-ACC radiometers the non-linearity $\varepsilon_{\tau}(DN_i(\lambda, d_i, \tau_0))$ due to integration time is within $\pm 0.25\%$ and reduces to $\pm 0.1\%$ for wavelengths shorter than 750 nm. These results are supported by the theoretical determination of non-linearity contributions $\varepsilon_{\tau}(\tau, t_0)$ as a function of the readout time $t_0$ (see the black lines in figure 6).
3.1.4 Impact of the non ideal cosine response of collectors on non-linearity characterizations.

In view of assessing the impact of the non ideal cosine response of irradiance collectors on non-linearity characterizations of RAMSES-ACC radiometers, linear regression coefficients $a(\lambda)$ of the non-linearity factors $\varepsilon [DN(\lambda, d_i, \tau_0)]$ of SAM-8516, and related standard deviations (error bars) as a function of the output counts.

Results are shown in red in figure 7, superimposed to those obtained with normal incidence as indicated by the errorbars in figure 7. Differences between the two measurement configurations are generally on the order of the standard deviation of the measurements performed with normal incidence as indicated by the errorbars in figure 7.

This finding indicates the negligible effects of the non ideal cosine response of the collector on the characterization of the non-linearity of the radiometers considered, which supports the independence of linearity response from the radiometric foreoptics.

Figure 4. Average values $\bar{a}(\lambda)$ (solid line) of the coefficients $a(\lambda)$ corresponding to three independent characterizations of the non-linearity factors $\varepsilon [DN(\lambda, d_i, \tau_0)]$ of SAM-8516, and related standard deviations (error bars) as a function of the output counts.

Figure 7. Coefficients $a(\lambda)$ and $\bar{a}(\lambda)$ for SAM-8516 determined with $20^\circ$ tilted angle of the incoming flux (in red) superimposed to the average values and standard deviations of the corresponding values obtained with normal incidence (in black).

Figure 5. Residual Non-linearity $\varepsilon [DN(\lambda, d_i, \tau_0)]$ of SAM-8516 after the application of the non-linear corrections using the coefficients $\bar{a}(\lambda)$. Colors identify the wavelength.

Figure 6. Non-linearity $\varepsilon [DN(\lambda, d_i, \tau_0)]$ due to integration time $\tau_i$ as determined for SAM-8516. Colors identify the wavelengths. The black lines represent the non-linearity contribution $\varepsilon_r(\tau_i, t_r)$ computed with values of the readout time $t_r$ equal to 0.01 ms and 0.5 ms (thin lines), and 0.25 ms (thick line).

Figure 8. Coefficients $\bar{a}(\lambda)$ for SAM-82C1, SAM-835C, SAM-84C0, and SAM-8516. Their average value $\bar{a}(\lambda)$ (solid line) and the related standard deviation (errorbars) determined from all characterizations, are shown in grey.

3.14 Impact of the non ideal cosine response of collectors on non-linearity characterizations. In view of assessing the impact of the non ideal cosine response of irradiance collectors on non-linearity characterizations of RAMSES-ACC radiometers, linear regression coefficients $a(\lambda)$ of the non-linearity factors $\varepsilon [DN(\lambda, d_i, \tau_0)]$ were determined applying measurements performed with an angle of $20^\circ$ between the incoming flux and the normal to the collector plane. Results are shown in red in figure 7, superimposed to those obtained with normal incidence displayed in black. Differences between the two measurement configurations are generally on the order of the standard deviation of the measurements performed with normal incidence as indicated by the errorbars in figure 7. This finding indicates the negligible effects of the non ideal cosine response of the collector on the characterization of the non-linearity of the radiometers considered, which supports the independence of linearity response from the radiometric foreoptics.
3.2. Non-linearity corrections for the class of RAMSES radiometers

Results related to correction coefficients $\hat{a}(\lambda)$ of the four RAMSES-ACC included in this study are displayed in figure 8 together with their average values $\overline{a}(\lambda)$ and standard deviations. Data indicate a remarkable agreement across the various radiometers. Notable is also the lack of values for SAM-84C0 between 600 nm and 630 nm, as well as their departure from those obtained with the other radiometers around 590 nm and 640 nm as a result of the saturation of the detector array in that specific spectral range during its characterization. The same considerations apply for the interval 450 nm–480 nm and for radiometers SAM-8516 and SAM-82C1. Nevertheless, it is noticed that due to the specific features of the different radiometers, the merging of results from various units permits to expand the spectral range of $\hat{a}(\lambda)$ values obtainable from individual characterizations.

3.3. Impact of non-linearity on $R_{rs}(\lambda)$ from natural waters

The output counts determined during field measurements and laboratory calibrations for the three sample spectra introduced in section 2.4, are displayed in the left column of figure 9. By indicating with $\mathcal{I}(\lambda)$ the radiometric quantities measured in the field to support both above- and in-water measurement methods applied for the determination of $R_{rs}(\lambda)$, the resulting
non-linearity factors $\varepsilon_\lambda$ are displayed in the right column of figure 9. Measurements corresponding to typical natural water spectra exhibiting their maxima below 450 nm, around 500 nm, and above 550 nm are indicated as type-A, type-B, and type-C, and are shown in the top, middle and bottom rows, respectively (see figure 10).

For the three sample cases, $\varepsilon_\lambda$ exhibits values ranging between $-0.9\%$ and $+1.8\%$, higher at longer wavelengths consistently with $\hat{a}(\lambda)$. Recalling that $\varepsilon_\lambda$ is a function of the difference between the output counts measured during calibration and field measurements for each radiometric quantity $\lambda$, it is remarked that while the former measurements are obtained in a controlled context and are characterized by spectral values slightly changing across independent calibrations, the latter are generally performed in a highly variable environment and vary with both illumination conditions and optical properties of the water. Notably, type-A and type-B spectra exhibit similar values of $\varepsilon_\lambda$ in the 450 nm–800 nm spectral interval for the various radiometric quantities. On the contrary, type-C spectra show values of $\varepsilon_\lambda$ marked by pronounced count values of $L_T$ and $L_i$ nearly 570 nm, and by relatively low values of $E_\lambda$ solely resulting from the illumination conditions and the integration time applied.

In line with with (14) and (15), the non-linearity factors determined for $R_{\lambda}$ applying above- and in-water measurement methods, $\varepsilon[R_{\lambda}^a(\lambda)]$ and $\varepsilon[R_{\lambda}^i(\lambda)]$, depend on radiance to irradiance ratios. With reference to figure 11, type-A and type-B $R_{\lambda}$ spectra characterized by very different values of the radiance and irradiance counts across most of the spectrum, exhibit non-linearity effects of the same order of the maximum non-linearity affecting the contributing radiometric quantities: i.e. they show corrected values up to 2% lower than the uncorrected ones at 600 nm where the differences between counts of radiance and irradiance values are the largest (see figure 9). Conversely, when considering the type-C $R_{\lambda}$ spectrum, closer counts and non-linearity factors characterize the radiance and irradiance values across most of the spectrum. This leads to a partial reduction of the non-linearity effects, which exhibit values of both $\varepsilon[R_{\lambda}^a(\lambda)]$ and $\varepsilon[R_{\lambda}^i(\lambda)]$ within $\pm1\%$, higher at 570 nm in correspondence to the maxima of $\varepsilon[L_T(\lambda)]$ and of $\varepsilon[L_i(\lambda)]$. The impact of non-linearity quantified through the absolute differences $\Delta[R_{\lambda}^a(\lambda)]$ and $\Delta[R_{\lambda}^i(\lambda)]$ (not shown) varies between $-0.08 \times 10^{-3}$ sr$^{-1}$ and $+0.03 \times 10^{-3}$ sr$^{-1}$, and between $-0.06 \times 10^{-3}$ sr$^{-1}$ and $+0.09 \times 10^{-3}$ sr$^{-1}$ for above-water and in-water measurements, respectively.

Relative and absolute uncertainties characterizing $R_{\lambda}$ resulting from the application of radiometric quantities affected by non-linearity, were estimated considering the entire measurement dataset. The contributions to relative uncertainties are always lower than 1.5%, and reduce to 0.7% for those $R_{\lambda}$ spectra exhibiting maxima beyond 550 nm. Excluding the values determined for these latter below 590 nm, larger values of relative uncertainty were obtained for above-water measurements with respect to the in-water ones. The lowest absolute uncertainties, i.e. lower than 0.025 $\times 10^{-3}$ sr$^{-1}$, were determined with $R_{\lambda}$ spectra characterized by maxima below 450 nm, while the highest, i.e. 0.07 $\times 10^{-3}$ sr$^{-1}$, for spectra exhibiting maxima above 550 nm. Intermediate results were obtained for $R_{\lambda}$ spectra with maxima around 500 nm. The above values are relevant to assign uncertainties to $R_{\lambda}$ values determined with RAMSES radiometers not corrected for non-linearity of response.
entire class of RAMSES radiometers. Results obtained for the 450 nm–800 nm spectral range show uncertainties slightly increased with respect to those affecting characterizations of individual units (as indicated by the maximum value of the standard deviation of correction coefficients increasing from $0.05 \times 10^{-6}$ in figure 4 to $0.1 \times 10^{-6}$ in figure 8). Moreover, considering the expected relatively small values of $\hat{a}(\lambda)$ below 450 nm, their extrapolation in the 400 nm–450 nm interval from the actual determinations performed in the 450 nm–550 nm interval can be envisaged for operational applications.

Additional element requiring some discussion is the impact of non-linearity on $R_{ns}(\lambda)$ from natural waters. As already stated, $R_{ns}(\lambda)$ results from the ratio of radiance to irradiance values. Thus as shown in figure 11, the resulting non-linearity corrections vary with the differences between their count values which depend on the spectral features of the various quantities. Measurement strategies aiming at minimizing the impact of non-linearity in data products such as $R_{ns}(\lambda)$, should then maximize the comparability of counts between the radiometric quantities to be rationed in the spectral regions of particular interest.

5. Summary and conclusions

The non-linearity of RAMSES hyperspectral radiometers widely used by the scientific community to support satellite ocean color applications was evaluated in the spectral interval 450 nm–800 nm by performing a series of measurements at various distances from a stable source. Distance offsets affecting both the sensor and the source reference planes were evaluated and accounted for in the characterizations. Both the integration time and the non ideal cosine response of the radiometer collectors demonstrated to have negligible impact on the characterization of non-linearity factors. Results from the analysis of four RAMSES-ACC irradiance sensors indicate non-linearities within $\pm1.5\%$ more pronounced at the longer wavelengths. For the various elements of the detector array of each radiometer considered in the study, a linear fit was applied to model the non-linearity and to determine spectral correction coefficients. Finally, by extending the previous findings to both RAMSES irradiance and radiance units, the impact of non-linearity was evaluated on sample $R_{ns}(\lambda)$ collected during clear sky conditions and calm sea in European Seas exhibiting diverse optical characteristics. Results indicate an increase of the uncertainty resulting from the non-removal of non-linearity effects generally lower than 1.5% for both $R_{ns}(\lambda)$ determined applying above- and in-water measurement methods. These relative uncertainties correspond to absolute uncertainties $u_a[R_{ns}(\lambda)]$ always lower than $0.07 \times 10^{-3}$ sr$^{-1}$.

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## Appendix. List of symbols, definition and units

| Symbol | Definition | Unit |
|--------|------------|------|
| $a$    | Linear regression coefficient of the non-linearity factor $\varepsilon$ as a function of the output counts $DN$ | counts$^{-1}$ |
| $\bar{a}$ | Average of the $a$ values from independent characterizations of a single radiometer | |
| $\hat{a}$ | Average of the $\bar{a}$ values from all the radiometers | |
| $d$    | Distance between the front plate of the radiometer and lamp posts | mm |
| $d_R$  | Reference distance corresponding to $DN_R$ output counts | mm |
| $d_i$  | Distance applied for the $i$th measurement sequence | mm |
| $\delta$ | Distance between lamp posts and its radiating reference plane | mm |
| $\bar{\delta}$ | Distance between front plate of the radiometer and its receiving reference plane | mm |
| $\bar{\delta}$ | Spectrally averaged $\delta$ | mm |
| $\delta$ | $\delta_s + \delta_r$ | mm |
| $D$    | Distance applied for the FEL lamp calibration | mm |
| $DN$   | Radiometer output | counts |
| $DN_i$ | Radiometer output from the $i$th measurement sequence | |
| $DN_L$ | Radiometer output corrected for non-linearity of response | |
| $DN_R$ | Radiometer reference output in the range of $27 \times 10^3$–$33 \times 10^3$ counts | |
| $\Delta$ | Impact of non-linearity in absolute terms for radiance, irradiance and remote sensing reflectance | mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$ (rad.) |

### Radiometric Quantity

- $E_r$: Reference irradiance
- $E_d$: Total downward irradiance at the sea surface
- $e$: Residual non-linearity
- $\varepsilon$: Non-linearity factor
- $\varepsilon_T$: Non-linearity due to integration time
- $\varepsilon_r$: Non-linearity due to readout time
- $\bar{\varepsilon}_L$: Estimated non-linearity factor determined from the application of $\bar{a}$
- $I$: Radiant intensity
- $\Im$: Generic radiometric quantity (i.e. $L_T$, $L_a$, $L_u$, or $E_d$)
- $L_T$: Total radiance from the sea surface
- $L_a$: Sky radiance
- $L_u$: Sub-surface upwelling radiance
- $\lambda$: Wavelength
- $\lambda_0$: Reference wavelength (i.e. 600 nm)
- $m$: Parameter accounting for the geometrical properties of the radiometer collector response
- $N$: Number of $R_{rs}$ spectra exhibiting equivalent spectral features
- $p$: Parameter accounting, jointly with $q$, for the angular distribution of the source flux
- $q$: Parameter accounting, jointly with $p$, for the angular distribution of the source flux
- $r_s$: Equivalent source radius
- $r_t$: Equivalent radiometer aperture radius
- $r_0$: Radiometer aperture radius
- $R_s$: Remote sensing reflectance
- $R_{rs}$: Remote sensing reflectance obtained from above-water measurements
- $R_{i}$: Remote sensing reflectance obtained from in-water measurements
- $\Re$: Actual spectral responsivity of radiance and irradiance sensors
- $\Re_0$: Ideal spectral responsivity of radiance and irradiance sensors
- $\tau$: Integration time
- $\tau_i$: Integration time applied for the $i$th measurement sequence
- $u_t$: Relative uncertainty due to non-linearity
- $u_a$: Absolute uncertainty due to non-linearity
- $x_0$: Equivalent horizontal dimension of the FEL lamp filament
- $y_0$: Equivalent vertical dimension of the FEL lamp filament
- $t_r$: Readout time
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