Reduction of non-linearity effects for a class of hyper-spectral radiometers

Marco Talone\textsuperscript{1,\dagger}, Giuseppe Zibordi\textsuperscript{1} and Agnieska Bialek\textsuperscript{2}

\textsuperscript{1} Joint Research Centre, European Commission, Ispra, Italy
\textsuperscript{2} National Physical Laboratory, Teddington, United Kingdom

E-mail: marco.talone@ec.europa.eu

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Abstract

We determined the non-linearity coefficients of RAMSES hyper-spectral radiometers by relying on measurements performed at two distances from a reference source, i.e. $d_C$ and $\sqrt{2}d_C$, leading to equivalent digital counts in a large portion of the spectrum when doubling the integration time. Results from the proposed two-distance method are comparable to those obtained through a comprehensive characterization based on multi-distance measurements. Specifically, the differences between the non-linearity coefficients obtained from the two characterization approaches exhibit values lower than their respective standard deviations over most of the spectral range, except for the blue spectral region due to operational limits of the multi-distance method. This finding supports the use of the simpler two-distance method for the characterization of the non-linearity coefficients of individual instruments, opposite to the application of the non-linearity coefficients recently recommended for the entire class hyperspectral radiometers matter of this investigation.

Keywords: non-linearity, hyper-spectral radiometry, ocean colour

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

1. Introduction

Sensor non-linearity is a significant source of uncertainty for radiometric measurements. Because of this, best practice suggests its determination on a instrument to instrument basis. However, comprehensive characterizations of sensors non-linearity may imply dedicated and time consuming laboratory efforts.

A previous investigation \cite{1} extensively addressed non-linearity effects for a series of hyper-spectral radiometers widely used by the ocean colour scientific community, i.e. RAMSES manufactured by TriOS Mess-und Datentechnik GmbH (Rastede, Germany). The study, which applied measurements of a stable source at 12 different distances, \textit{i}. showed a general linear dependence of spectral non-linearity factors with the digital counts $DN$ over most of the spectral range (excluding the blue region challenged by the low sensitivity of the detector and the low flux from the source), \textit{ii}. demonstrated the negligible dependence of non-linearity with integration time and finally, \textit{iii}. provided reference values of non-linearity correction coefficients for the specific class of instruments. Still, these reference values are based on the characterization of a relatively small number of radiometers (i.e. 4), which suggests the need to verify their suitability for those RAMSES radiometers aiming at supporting applications requiring low measurement uncertainty. Within such a general context, this work proposes a simplified method for the characterization of radiometers nonlinearity solely relying on measurements performed at two different distances from a source. The performance of the method and the impact of the derived non-linearity factors on the determination of the remote-sensing reflectance for natural waters is investigated for various water types.
2. Materials and methods

2.1. Radiometers

As already mentioned, this study focuses on the characterization of a specific class of hyperspectral radiometers, i.e. RAMSES. These embrace radiance (i.e. RAMSES-ARC) and irradiance (i.e. RAMSES-ACC) radiometers. Both are based on ZEISS (Oberkochen, Germany) Monolithic Miniature Spectrometer-1 (MMS-1) built on the Hamamatsu (Ichino-cho, Japan) S3904 256-channel NMOS array coupled to a fiber bundle connected to the foreoptics module. This latter consists of a condenser lens defining a full-angle-field-of-view of approximately $7^\circ$ for RAMSES-ARC units, and a cosine collector of $3.5\,\text{mm}$ radius for RAMSES-ACC units. RAMSES measurements span over the nominal $320-950\,\text{nm}$ range with spectral sampling and resolution of approximately $3.3\,\text{nm}$ and $10\,\text{nm}$, respectively. The integration time can vary between $4\,\text{ms}$ and $8192\,\text{ms}$ depending on the illumination conditions.

A former study [1] showed that the non-linearity of RAMSES radiometers is generally comprised within $\pm 1.5\%$, with values more pronounced at the longest wavelengths. It is anticipated that this study will mostly rely on a specific RAMSES-ACC irradiance sensor identified by its serial number SAM-8516. Still, results have been assessed using various radiometers from the same class of sensors.

2.2. Standard spectral irradiance calibration protocol

Spectral irradiance calibrations should be performed relying on NMI (National Measurement Institute) traceable standards (e.g. calibrated FEL 1000W lamps) [2]. Lamp and sensor must be carefully aligned, with this latter positioned at a distance $d$ (e.g. $d = d_{c}$ with $d_{c} = 50\,\text{cm}$ applied for standard FEL calibrations) along the optical path between the collector front plate and the lamp posts. The lamp must be baffled and draped so that the out-of-direct-path flux received by the sensor is minimized. For each wavelength $\lambda$, calibration requires measurements of: i. the ambient light at $d_{c}$ (i.e. $\text{DN}_{B}(\lambda, d_{c}, \tau_{B})$), performed with integration time $\tau_{B}$ and with the direct optical path between lamp and sensor obstructed by an occulting device (e.g. a rod); and ii. the lamp irradiance at $d_{c}$ (i.e. $\text{DN}_{S}(\lambda, d_{c}, \tau_{C})$) performed with integration time $\tau_{C}$ with the optical path between lamp and sensor free from obstacles.

The former measurements corrected for the dark signal contribution $\text{DN}_{D}(\lambda, d_{c}, \tau_{C})$ and $\text{DN}_{D}(\lambda, d_{c}, \tau_{B})$ obtained with the entrance optics fully closed (i.e. $\text{DN}_{B}(\lambda, d_{c}, \tau_{B}) = \text{DN}_{B}(\lambda, d_{c}, \tau_{B}) - \text{DN}_{D}(\lambda, d_{c}, \tau_{B})$) and $\text{DN}_{S}(\lambda, d_{c}, \tau_{C}) = \text{DN}_{S}(\lambda, d_{c}, \tau_{B}) - \text{DN}_{D}(\lambda, d_{c}, \tau_{C})$ are then applied to compute the spectral calibration coefficients $F_{E}(\lambda, d_{c}, \tau_{C})$ according to:

$$F_{E}(\lambda, d_{c}, \tau_{C}) = \frac{\text{DN}(\lambda, d_{c}, \tau_{C})}{E_{C}(\lambda, d_{c})},$$

(1)

where $\text{DN}(\lambda, d_{c}, \tau_{C}) = \text{DN}_{S}(\lambda, d_{c}, \tau_{C}) - \text{DN}_{D}(\lambda, d_{c}, \tau_{B}) \times \frac{\tau_{C}}{\tau_{B}}$ and $E_{C}(\lambda, d_{c})$ is the lamp irradiance equal to $I(\lambda)/d_{c}^{2}$ with $I(\lambda)$ the lamp radiant intensity.

It is recalled that (1) relates the lamp radiant intensity to the signal measured by the radiometer under the assumptions of non-attenuating transmission medium, point source, and point sensor. While the first assumption can be confidently applied in a laboratory measurement context, the last two may require additional consideration especially for short sensor-to-source distances. In agreement with [4] and [5], for cosine collectors and FEL lamps the finite dimensions of source and sensor are accounted for by replacing the geometric distance $d$ with the equivalent distance $D = \sqrt{d^{2} + r_{r}^{2} + r_{r}^{2}}$, where $r_{r}$ and $r_{r}$ are defined as:

$$r_{r} = 0.5 \sqrt{0.5 x_{0}^{2} + 1.34 y_{0}^{2}},$$

(2)

and

$$r_{r} = 1.17 r_{0},$$

(3)

with $r_{0}$ radius of the irradiance collector and $x_{0}$ and $y_{0}$ horizontal and vertical dimensions of the lamp filament, respectively.

2.3. Two-distance measurements

The calibration procedure described in section 2.2 was applied to measurements performed on a 2 m calibration bench at distances $d_{i}$ equal to $50\,\text{cm}$ (i.e. $d_{c}$) and $72\,\text{cm}$ (i.e. $\approx \sqrt{3}d_{c}$). The radiometers were aligned with respect to an FEL 1000W quartz-halogen tungsten coiled filament lamp [3] with the aid of an alignment jig and a laser. The same integration time $\tau_{C}$, autonomously determined by the radiometer to maximize the digital counts obtained at $d_{c}$, was applied for both measurements. In addition, the measurement at $d = 72\,\text{cm}$ was repeated with integration time $2\tau_{C}$. Finally, two supplementary measurements were performed with integration time $\tau_{C}$ at $d = 60\,\text{cm}$ and $d = 85\,\text{cm}$ for verification purposes. The applied distances and integration times as well as the corresponding expected digital counts are reported in table 1, while a schematic of the measurement setup is shown in figure 1.

Measured values in digital counts are shown in figure 2 as a function of the wavelength for each combination of distance and integration time listed in table 1. By relying on these parameters, the characterization method for non-linearity develops into two steps: first, measurements identified by the indices $i = 1$ and $i = 3$ are used to determine the exact sensor-to-lamp distance depending on the computing position.
Figure 1. Schematic of the measurement setup.

Figure 2. Digital counts measured at different distances and integration times for each case listed in table 1.

of the equivalent sensor-receiving and lamp-emission planes (see section 2.4); second, the non-linearity factor is calculated as the percentage difference between the calibration factors obtained with the measurements identified by the indices $i = 1$ and $i = 2$ applying the corrected distances (see section 2.5). It is recalled that the measurements performed with the indices $i = 4$ and $i = 5$ are only applied to verify the consistency of the non-linearity correction coefficients formerly determined at different distances and for diverse incoming fluxes.

2.4. Determination of the exact source-sensor distance

An accurate determination of the sensor-to-lamp distance requires the quantification of the combined offsets due to the difference between the collector front plate and the effective receiving plane $\delta_s(\lambda)$, and, between lamp posts and the effective irradiance plane $\delta_l(\lambda)$ [4, 5]. As already anticipated, this is obtained by exploiting the measurements identified by the indices $i = 1$ and $i = 3$ in table 1. That specific combination of distances and integration times, in fact, ensures close digital counts at the two distances, and consequently minimizes the impact of non-linearity. This, together with the assumption of negligible impact of integration time on non-linearity formerly verified for TriOS RAMSES [1], permits to ascribe the difference between $DN_1$ and $DN_3$ entirely to the distance offsets. Specifically, for each wavelength, the distance offset $\delta(\lambda) = \delta_s(\lambda) + \delta_l(\lambda)$ is estimated by solving the equivalence:

$$DN_3(\lambda, d_3, \tau_3)[(d_3 + \delta(\lambda))^2 + r_3^2 + r_s^2]$$

$$= \frac{DN_1(\lambda, d_1, \tau_1)[(d_1 + \delta(\lambda))^2 + r_1^2 + r_s^2]}{\tau_3}.$$  (4)

The 500 nm–600 nm spectral interval exhibiting relatively high spectral sensitivity by the radiometer and high flux by the source was selected to determine the mean $\delta$ of the $\delta(\lambda)$ values applied in any successive processing step.

2.5. Determination of the non-linearity factor

The non-linearity factor $\varepsilon(\lambda)$ is calculated by applying the corrected distances $d'_1$ and $d'_2$ to the determination of the calibration coefficients $FE(\lambda, d'_1, \tau_1)$, as:

$$\varepsilon(\lambda) = \frac{[FE(\lambda, d'_2, \tau_2) - FE(\lambda, d'_1, \tau_1)]}{FE(\lambda, d'_1, \tau_1)},$$  (5)

with $\tau_1 = \tau_2 = \tau_c$, $d'_i = \sqrt{(d_i + \delta)^2 + r_3^2 + r_s^2}$ for the index $i = 1$ or $i = 2$, and $\delta$ the average distance offset defined in section 2.4.

Finally, for each wavelength, the correction coefficient $a(\lambda)$ is defined as the ratio between the resulting non-linearity factor $\varepsilon(\lambda)$ and the difference between corresponding digital counts:

$$a(\lambda) = \frac{\varepsilon(\lambda)}{[DN_2(\lambda, d'_2, \tau_2) - DN_1(\lambda, d'_1, \tau_1)]}.$$  (6)

3. Results

3.1. Exact source-sensor distance

The distance offsets $\delta(\lambda)$ obtained from the characterization of SAM-8516 applying the scheme detailed in section 2.4 are shown in figure 3. Consistently with results from a previous analysis [1], they vary between approximately 2.3 and 3.7 mm across the 400 nm–800 nm spectral range, with an average value of 2.9 mm and a standard deviation of 0.2 mm over the
500 nm–600 nm spectral interval. Two additional independent characterizations performed for the same sensor, exhibited average values of 2.4 ± 0.3 mm and 3.3 ± 0.3 mm. Notable is the pronounced spectral dependence of \( \delta (\lambda) \), appreciably larger than that illustrated in [1]. This is mostly due to the impact of sensor non-linearity affecting the difference between digital counts of measurements identified by the indices \( i = 3 \) and \( i = 1 \) in table 1. It is specifically caused by the difference between the values of the actual distance \( d_3 \) and the exact value of \( \sqrt{2} d_i \), i.e. 72 cm versus 70.7 cm. This finding further remarks the importance of an accurate choice of the sensor distances for its characterization.

### 3.2. Non-linearity factor

The linear fits of the calibration factors with respect to the digital counts from measurements indexed by \( i = 1 \) and \( i = 2 \) in table 1 (i.e. the coefficients \( a(\lambda) \)), are illustrated in blue in figure 4. The solid line and error bars represent the average values and standard deviations of three independent realizations. Equivalent coefficients formerly determined for the same radiometer through multi-distance measurements [1] are superimposed in gray, with the dashed line between 400 nm and 480 nm indicating extrapolated values of \( a(\lambda) \) from the 480–550 nm spectral interval. It is recalled that such an extrapolation was suggested by the need to overcome the lack of values from the multi-distance characterization in the specific spectral interval.

Results show that the two characterization methods (i.e. that relying on multi-distance measurements [1] and that solely based on two distances proposed here) exhibit values of the coefficient \( a(\lambda) \) agreeing within \( 0.02 \times 10^{-6} \) counts\(^{-1}\) beyond 550 nm. Differences are larger at shorter wavelengths with values of \( 0.07 \times 10^{-6} \) counts\(^{-1}\) at 500 nm increasing to \( 0.25 \times 10^{-6} \) counts\(^{-1}\) at 400 nm. These larger differences in the blue spectral region are explained by the uncertainties resulting from the very small differences between \( DN_i \) and \( DN_i \) due to both a lower sensitivity of the spectrometer and the relatively low flux from the source. These digital values, in fact, never exceed 7000 counts (see figure 2), and their accurate determination depends on the accuracy of the estimated thermal noise exhibiting values in the range of 2000–3000 counts. The larger \( DN \) differences applied in [1], explained by the wider range of distances, permit a more accurate determination of the radiometer non-linearity over the entire dynamic range, and are the source of the disagreement observed between the values of \( a(\lambda) \) from the two methods in the 480–540 nm spectral interval. Because of this, the comparison between results from the two methods should be restricted to values determined at wavelengths tentatively beyond 500 nm.

Still, the equivalent standard deviation of \( 0.03 \times 10^{-6} \) counts\(^{-1}\) determined with the two-distance and multi-distance methods together with the standard deviation of approximately \( 0.05 \times 10^{-6} \) counts\(^{-1}\) affecting the values of \( a(\lambda) \) proposed for the class of RAMSES radiometers [1], support the application of the two-distance method for the characterization of individual RAMSES non-linearity without any significant loss of information with respect to the application of the class-based \( a(\lambda) \) determined with the multi-distance method.

The consistency of the non-linearity factors previously described, was verified using the calibration coefficients determined with the measurements indexed by \( i = 4 \) and \( i = 5 \), and applying the correction coefficients \( a(\lambda) \). The difference between the calibration coefficients determined with the measurements indexed by either \( i = 4 \) (or \( i = 5 \)) and \( i = 1 \), with respect to the nominal values obtained for \( i = 1 \), are computed as \( e_i(\lambda) = |F_E(\lambda, d'_i, \tau_i) - F_E(\lambda, d'_1, \tau_1)|/F_E(\lambda, d'_1, \tau_1) \) and are shown in figure 5(a). Residual differences after the application of the derived non-linearity corrections, instead, are displayed in figure 5(b) as:

\[
e_i(\lambda) = |F'_E(\lambda, d'_i, \tau_i) - F_E(\lambda, d'_1, \tau_1)|/F_E(\lambda, d'_1, \tau_1),
\]

with \( F'_E(\lambda, d'_i, \tau_i) = a(\lambda) \times [DN_i(\lambda, d'_i, \tau_i) - DN_i(\lambda, d'_1, \tau_1)] \times F_E(\lambda, d'_1, \tau_1) \).
Results exhibit percent differences up to 2% between the nominal calibration factors and those indicated by either $i = 4$ or $i = 5$, which reduce to values generally lower than 0.1% after non-linearity corrections. This finding along with validating the estimated non-linearity factors, also indicates their independence from the measurement distance, confirming the possibility of applying distances different from $d_C$ for sensors characterization.

4. Discussion

4.1. Impact of non-linearity on $R_{rs}$ spectra of natural waters

The error on the remote-sensing reflectance $R_{rs}(\lambda)$ determined from natural waters resulting from sensor non-linearity was assessed using sample field measurements acquired with RAMSES radiometers in the Western Black Sea and the Central Mediterranean Sea. Consistently with a previous analysis [1], the selected spectra refer to three typical water types exhibiting maximum reflectivity in the blue, green, and yellow spectral regions, indicated as type-A, -B, and -C in figure 6.

Assuming that the linearity of radiometers is not affected by the sensor foreoptics [1], the results obtained from the analysis of RAMSES-ACC irradiance units are here extended to the RAMSES-ARC radiance ones. This allows to estimate the impact of non-linearity correction coefficients $a(\lambda)$ on $R_{rs}(\lambda)$ by applying the two-distance calibration scheme. Specifically, neglecting higher-order contributions, non-linearity factors $\varepsilon(\lambda)$ have been calculated for any of the radiometric quantities $\Im(\lambda)$, i.e. the total downward irradiance at the surface, the total radiance from the sea, the sky radiance, or the sub-surface upwelling radiance, used to compute the remote-sensing reflectance (see [1] for details) as:

$$\varepsilon(\lambda) \approx a(\lambda)[DN_{3,F}(\lambda) - DN_{3,C}(\lambda)],$$  \hspace{1cm} (8)

where the subscripts $F$ and $C$ specify measurements acquired in the field or during the sensor calibration.

The impact of non-linearity on the remote-sensing reflectance indicated by $\varepsilon[R_{rs}(\lambda)]$ is given by the composition of the various $\varepsilon(\lambda)$. Finally, the residual percentage non-linearity $\varepsilon(\lambda)$ is defined as the difference between $\varepsilon[R_{rs}(\lambda)]$ obtained relying on coefficients $a(\lambda)$ determined through the multi- or two-distance sensor characterizations. Figures 7(a) and (b) display results obtained for both above-water and in-water data (see [1] for details on measurement methods). Specifically, figure 7(a) displays average errors between $-2\%$ and $+1\%$ resulting from the non-application of non-linearity corrections. Figure 7(b) shows differences between non-linearity corrections obtained with the multi-distance and two-distance characterization methods. These differences are typically within $+0.1\%$ and $-0.2\%$, decreasing between $0$ and $-0.1\%$ beyond $500$ nm where the multi- and two-distance characterizations exhibit best agreement (see figure 4).

4.2. Impact of distance offset $\bar{\delta}$

Sensor-to-lamp distances were corrected for the offsets due to the difference between nominal and effective receiving and emitting planes. As already anticipated, the sum of those two offsets resulted, on average, between $2.4$ mm and $3.3$ mm. To assess the impact on $R_{rs}(\lambda)$ of such a correction on the
evaluation of the sensor non-linearity, the calibration factors determined for the cases indexed by \( i = 1 \) and \( i = 2 \) were calculated with and without accounting for the distance offset. Additionally, for completeness, the impact of the correction for the finite dimensions of collector and lamp was also estimated.

The percentage residual \( e[R_{rs}(\lambda)] \) of non-linearity factor \( e[R_{rs}(\lambda)] \) obtained neglecting the distance offset \( \delta \), or the correction for the finite dimensions of collector and lamp are displayed in figures 8(a) and (b), respectively.

As shown in figure 8(a), the quantification of the distance offset is a relevant step of the non-linearity characterization. In fact, when neglected, it may lead to a significant underestimate of the sensor non-linearity effects (i.e. approximately 30% in the case of the radiometer considered in this study). On the contrary, the impact of the correction for the finite dimensions of collector and lamp does not exceed \( \pm 0.1\% \) in the blue spectral region and \( \pm 0.05\% \) beyond 500 nm (see figure 8(b)). This is explained by the very limited impact of the corrections on \( d'_i \) (i.e. smaller than 0.1% for \( d_i \geq 50 \) cm, as determined considering a 0.35 cm radius for the collector and a lamp filament with \( x_0 \) and \( y_0 \) equal to 0.8 and 2.0 cm, respectively).

4.3. Uncertainty estimate

To estimate a typical residual uncertainty due to sensor non-linearity after applying the correction based on the two-distance measurements with respect to the comprehensive multiple-distance one, a number of \( R_{rs} \) spectra of natural waters were used. Specifically, measurements were separated based on the water type, and relative and absolute uncertainties were then calculated for each of them as the root mean square of the differences between remote-sensing reflectance obtained applying the non-linearity factors determined with the two-distance method with respect to those from the multi-distance one. This method allowed to estimate the uncertainty contribution to the overall uncertainty in remote sensing reflectance.
due to residual uncertainties in non-linearity correction. It is emphasized that this is not the uncertainty of the non-linearity correction itself, but its impact on the uncertainty in remote sensing reflectance expressed in units of sr$^{-1}$. Results indicate a relative uncertainty always lower than 0.4%, decreasing with wavelength. In absolute terms, the uncertainty reaches its maximum at 400 nm, with values of $3 \times 10^{-5}$ sr$^{-1}$ for type-A water, $2 \times 10^{-5}$ sr$^{-1}$ for type-B water, and $1 \times 10^{-5}$ sr$^{-1}$ for type-C water, decreases with wavelength, and exhibits a slight dependence on the measurement method. These results satisfy uncertainty requirements for satellite ocean color validation implying that any individual contribution to the uncertainties of in situ data products (e.g., absolute calibration, temperature dependence, non-linearity, ...) is tentatively lower than 1%.

5. Conclusions

A two-distance characterization method was applied to further investigate the non-linearity of a hyper-spectral RAMSES radiometer. Measurements, still obtainable at any pair of distances exhibiting a $\sqrt{2}$ proportionality factor, were performed at 50 cm and 72 cm. Results indicate agreement in a large portion of the measurement spectrum with those obtained from a comprehensive characterization of the same sensor presented in a previous study and relying on multi-distance measurements [1]. Specifically, the differences between values of the non-linearity correction coefficients $a(\lambda)$ are within $\pm 0.02 \times 10^{-6}$ counts$^{-1}$ beyond 550 nm, increasing up to $0.2 \times 10^{-6}$ counts$^{-1}$ at 400 nm where both the radiometer sensitivity and the flux from the FEL source are the lowest. Still, the analysis shows that calibration factors can be corrected with residuals lower than 0.1% by applying the two-distance characterization approach.

By considering $R_{rs}$ spectra representative of different natural water types, the root mean of square differences between $R_{rs}$ obtained applying the non-linearity factors from the two alternative characterization approaches, exhibit values lower than 0.4%, corresponding to maximum absolute uncertainties of $3 \times 10^{-5}$ sr$^{-1}$ for waters characterized by a reflectance maximum in the blue spectral region. These differences are lower than those exhibited by radiometer-to-radiometer variability of coefficients $a(\lambda)$ [1], which suggests that the alternative two-distance method can be confident applied to determine instrument-specific non-linearity spectral factors with uncertainties typically lower than those affecting the class-based ones.

Finally, it is remarked that the method and the results presented in this study are only valid for RAMSES radiometers, for which the assumptions of linear dependence of the non-linearity factor with digital counts, and of negligible impact of integration time on non-linearity, were both previously verified [1]. The extension of the proposed method to other classes of radiometers would imply the prior verification of those assumptions.

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ORCID iDs

Marco Talone  @ https://orcid.org/0000-0002-9723-2080

References

[1] Talone M and Zibordi G 2018 Non-linear response of a class of hyper-spectral radiometers Metrologia 55 747–58
[2] IOCCG Protocol Series 2019 Protocols for satellite ocean color data validation: in situ optical radiometry IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 3.0 (Dartmouth, NS: IOCCG)
[3] Walker J H, Saunders R D, Jackson J K and McSparron D A 1987 NBS Measurement Services: Spectral Irradiance Calibrations vol 250-20 (Washington: NBS Special Publication) p 102
[4] Manninen P, Hovila J, Seppälä L, Kärhä P, Ylianttila L and Ikonen E 2006 Determination of distance offsets of diffusers for accurate radiometric measurements Metrologia 43 S120–4
[5] Manninen P, Kärhä P and Ikonen E 2008 Determining the irradiance signal from an asymmetric source with directional detectors: application to calibrations of radiometers with diffusers Appl. Opt. 47 4714–22