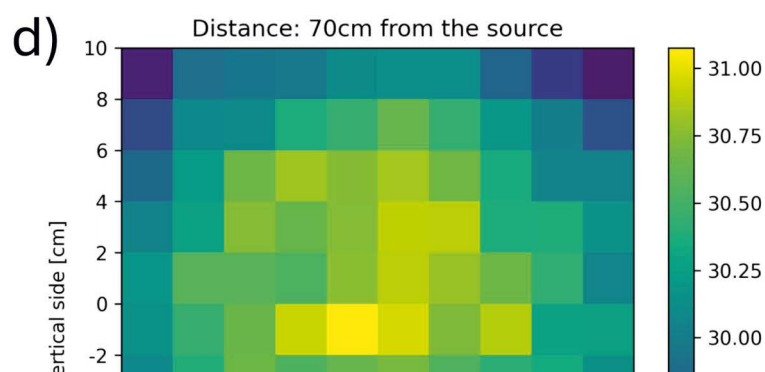
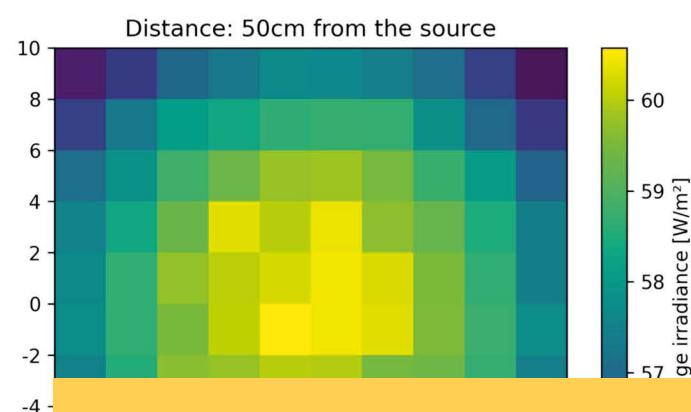
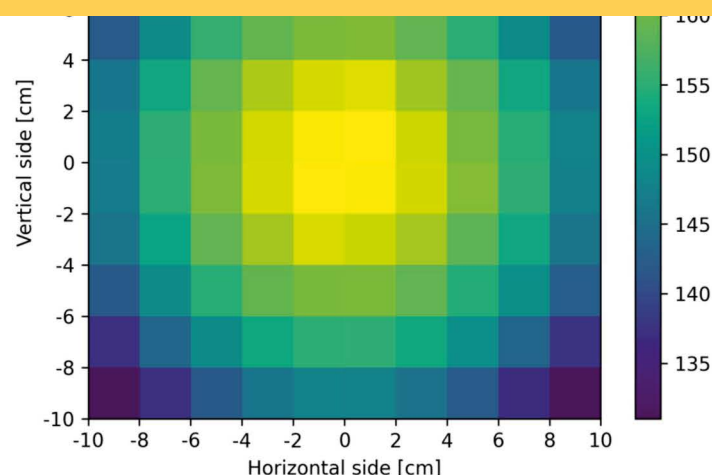
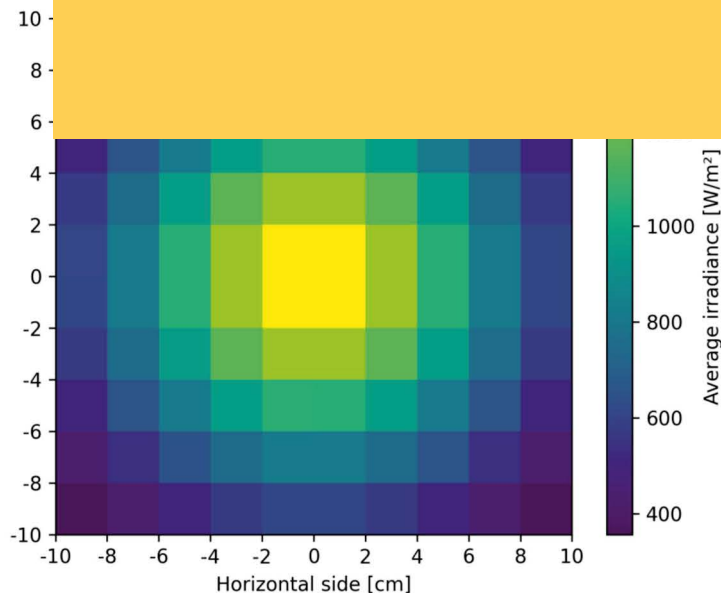




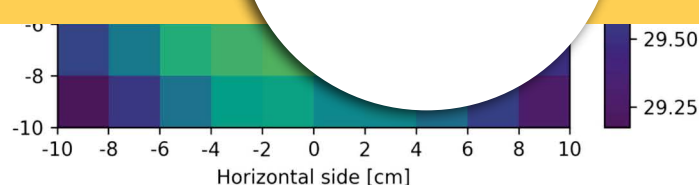
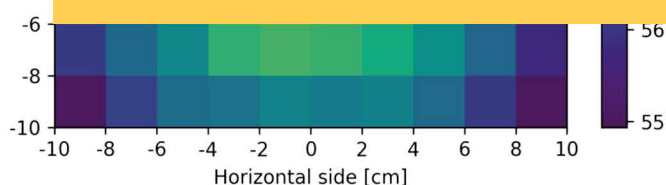
RAPPORTI TECNICI INGV

A calibration method for the
UV-Vis-NIR spectrometer installed
at the Thule High Arctic Atmospheric
Observatory (THAAO), Greenland



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RAPPORTI TECNICI INGV

A calibration method for the UV-Vis-NIR spectrometer installed at the Thule High Arctic Atmospheric Observatory (THAAO), Greenland

Angelica Focardi^{1,2,*}, Giovanni Muscari¹, Rita Asquini², Filippo Calì Quaglia¹, Monica Tosco^{1,3}, Massimo Mari¹, and Alcide di Sarra⁴

¹INGV | Istituto Nazionale di Geofisica e Vulcanologia, Sezione Roma 2, Italy

²Sapienza University of Rome, Department of Information Engineering, Electronics and Telecommunications, Italy

³Ca' Foscari University of Venice, Department of Environmental Sciences, Informatics and Statistics, Italy

⁴ENEA, Laboratory for Models and Measurements for Air Quality, and Climate Observations, Italy

*Corresponding author

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Cover Irradiance distribution on the surface of a plate (here extended to be 20 cm x 20 cm) at different distances | In copertina Distribuzione spaziale dell'irradianza sulla superficie di una piastra (20 cm x 20 cm) al variare della distanza

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Abstract

This document outlines the tools and processes involved in calibrating a RAMSES-ARC spectrometer manufactured by TriOS GmbH and used for measuring the atmospheric radiance in the Ultraviolet (UV), Visible (Vis) and Near Infrared (NIR) spectral ranges. Although calibration is essential for accurate measurements, it often involves high costs and specialized equipment. This document proposes a relatively simple, repeatable calibration procedure aimed at maintaining high accuracy while minimising costs. This work is particularly relevant for long term atmospheric monitoring in remote and harsh environments where consistency in calibration procedures are crucial.

This document also shows how the instrument's data are processed and the impact of the different calibration results on the acquired data. The spectrometer's fundamental characteristics, such as the background signal, have remained stable over the last 6 years. However, the correction function measured in this work and used to calibrate observed spectra produces spectral radiances that differ by 3%, on average, from those obtained by using the correction function measured 3 years ago with a different calibration setup. Additionally, both corrections (2025 and 2022) produce radiances that differ from those calculated by using the calibration function provided by the manufacturer in 2019 (by 9% and 6%, respectively). We studied the robustness of the calibration setup employed in this work and our findings show that the spectrometer's orientation relative to the main optical axis of the setup is the most significant factor influencing calibration accuracy. Small variations of a few centimetres in the distances of the reflectance panel from the spectrometer and from the baffles do not significantly affect acquisitions.

Keywords UV-Vis-NIR spectrometer calibration; Clouds optical thickness; Polar atmosphere

Introduction

A spectrometer measuring the UltraViolet (UV), Visible (Vis) and Near Infrared (NIR) radiation from the zenith direction has been used since August 2021, for radiance measurements at the Thule High Arctic Atmospheric Observatory, THAAO [1], located on the northwestern coast of Greenland, within the US Pituffik Space Base, formerly known as Thule Air Base. In order to understand the Earth system, it is important to understand how clouds affect the radiative energy balance along the atmospheric vertical profile and at the surface [Ceppi et al., 2017]. Their characteristics can be measured using in situ and ground-based instruments and, for example, spectral radiance measurements are useful for estimating cloud optical thickness [Cali Quaglia et al., 2024a; 2024b]. However, there is a lack of these ground-based measurements in the polar regions. High-quality measurements in extremely cold environments require rigorous and repeated calibration to ensure accuracy. The problem is that calibrations can be expensive, access to laboratories is limited and shipping instruments back to manufacturers for recalibration from remote locations such as the Arctic can be expensive and endanger the instrumentation [Schartmüller et al., 2024]. This highlights the need for a low-cost, in-house calibration approach that enables science teams in the field to conduct effective, regular and reliable calibrations.

This report presents a repeatable procedure for calibrating a spectrometer. The aim is to implement a robust setup along with a detailed procedure that can allow repeated standardized

calibrations over time. This will enable us to check the stability of the instrument and ensure consistent accurate measurements.

The report is organized as follows: in the first section all the components of the calibration setup are described; the definition and the description of the geometric setup are presented in the second section; in the third section there is the analysis of the impact of variations in the set-up and the evaluation of important signals and measurements, such as the dark signal and the ambient light; in the fourth section the data processing and the calibration procedure are discussed, with a final discussion on the spectral correction functions obtained during different calibrations over time.

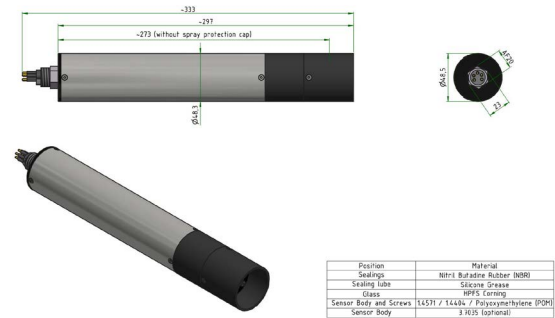
1. Instrumentation

RAMSES-ARC, a spectrometer manufactured by TriOS GmbH (Germany), is used for in situ hyperspectral measurements of radiance, $L(\lambda)$, with a Field Of View (FOV) of $\sim 7^\circ$ in air; the instrument and its dimensions are shown in Figure 1. It operates from 320 to 950 nm with a 3.3 nm channel spectral width, and a manufacturer-declared accuracy of better than 6%, dependent on λ [2]. The incoming light is detected by a photodiode array consisting of 256 pixels, 18 of which are dark pixels (from 237 to 254). The instrument's dynamic range goes from 0 to 65535 (2^{16} levels) due to its 16-bit electronic system. The spectrometer has 12 integration times available. The integration time is the duration over which the instrument collects light for a single measurement; shorter integration times generally result in noisier signals. When the instrument is in automatic acquisition mode, it automatically selects the optimal integration time to achieve a good signal-to-noise ratio while avoiding saturation. During the spectrometer's calibration and characterization process, we manually selected various integration times to study the response of the instrument in different conditions.

The calibration setup requires different components:

1. A calibration lamp (BN-LH250-V01 manufactured by Gigahertz Optik GmbH). It is a 250 W halogen lamp, with a temperature of 3300 K and illuminance of 2950 lx at 50 cm distance. The lamp was switched on at least 15 minutes before starting measurements to ensure sufficient warm-up time;
2. A highly stabilized current source (LPS-250 series manufactured by Gigahertz Optik GmbH) as the lamp requires a nominal working current of 10.500 A DC;
3. A 5×5-inch Labsphere Spectralon reflectance panel (model SRT-99-050) used as a uniform and near-Lambertian source of known radiance [Zibordi et al., 2019]. The panel reflectance was characterized by Labsphere with an 8° /hemispherical ($8^\circ/h$) spectral reflectance calibration over the 250–2500 nm range;
4. An optical bench composed by a metallic plate (1.10 m x 0.60 m x 1 cm) and custom supports designed and built at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) technical workshop to position and align each element of the setup.

Figure 1 RAMSES ARC spectrometer and its dimensions (in mm). Image from the TriOS RAMSES Technical Manual [2].



2. Setup geometry

The calibration setup was developed following published guidelines [Zibordi et al., 2019], which report the need for a uniform and near-Lambertian source of known radiance in order to calibrate sensors operating in the UV-Vis-NIR spectral range. A schematic representation of the setup developed and used is depicted in Figure 2.

The lamp is positioned in the direction perpendicular to the surface of the reflectance panel, which represents the main optical axis of the setup, pointing to the centre of the panel and placed at a distance r from it. The increase of r results in more uniform illumination over the panel's surface minimising the impact of inhomogeneity in the calibration process.

The spectrometer under calibration is placed at the same height of the main optical axis of the system, at an angle $\theta = 45^\circ$ with respect to it (Figure 2). It is essential to ensure that the instrument's FOV is fully illuminated by the reflected light coming from the panel and that the spectrometer itself does not obstruct the light path from the lamp to the panel.

Finally, baffles are used to minimise the amount of light that travels away from the main optical path, which might cause reflections on the chamber structures. These baffles are made of matte black cardboard and they ensure no shadows or diffraction edges on the panel. A more detailed description of the geometrical setup will be given in the next section.

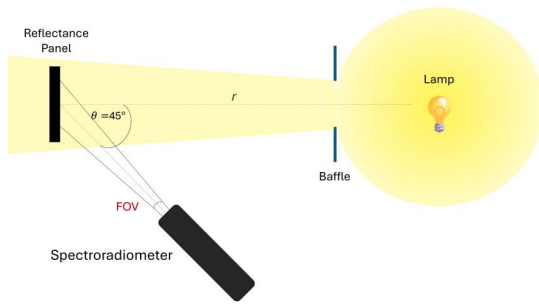


Figure 2 A diagram showing the chamber setup for radiance calibrations.

2.1 Lamp-Reflectance Panel distance

The first step is to determine the optimal distance for positioning the panel relative to the lamp to achieve uniform illumination. This distance was assessed both theoretically and by simulating the setup using the Ansys SPEOS software [3].

Lambert's law (Eq. 1) describes the illuminance under the assumption that the source is point-like, isotropic, and that the surface is flat and opaque [Johnson et al., 2014; Nucara & Pietrafesa, 2014]:

$$E = I \cdot \frac{\cos(\theta)}{r^2} \quad (1)$$

where:

- E is the irradiance [W/m²];
- I is the light intensity of the point source [W/sr];
- r is the distance between the light source and the point on the surface under consideration [m];
- θ is the angle between the surface normal and the direction of the light ray [rad].

Ansys SPEOS is an optical simulation software used to analyse lighting phenomena. In this work, it was used to simulate the irradiance distribution of a lamp at various distances to determine the optimal panel position.

The simulations allow us to evaluate the error introduced by the assumption that the light source is point-like and isotropic, as implied by Lambert's law, and to evaluate the actual luminous flux, I , produced by the source. The simulations use simplifications leading to the discretization of surfaces and the use of "rays" to model the Lambertian source.

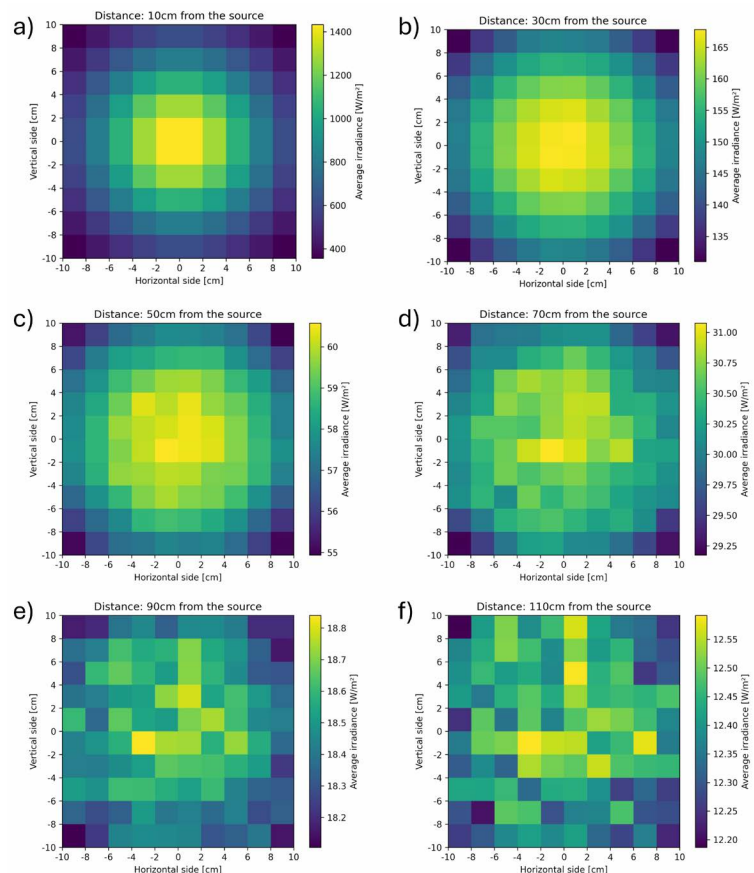
2.2 Light Source

We have simulated two different types of sources, spherical and cylindrical, to understand the impact of source shape on the results.

2.2.1 Spherical Source Shape

The first model developed consists of a spherical light source with a diameter of 2 mm, with each point on the surface emitting with Lambertian characteristics, approximating a point source. Based on the specifications of the lamp, its luminous flux was calculated and entered into the software as 9270 lumens. To further refine the model, the emission spectrum was incorporated into the source definition. The homogeneity of the irradiance field was estimated by simulating a 14 cm x 14 cm plate placed at an increasing distance from the light source. From the model output it is possible to obtain a visual representation of the increasing homogeneity of the irradiance field associated with the increasing distance of the reflectance panel from the light source (Figure 3). In the modelled representation, the panel is divided into 100 pixels with each pixel representing the average irradiance over its corresponding area. It is worth noticing that the irradiance scale of the various panels of Figure 3 changes significantly from panel to panel, ranging from 400 to 1400 W/m² (Figure 3a) and from 12.2 to 12.6 W/m² (Figure 3f).

Figure 3 Irradiance distribution on the surface of a plate (here extended to be 20 cm x 20 cm) at different distances: a) 10 cm, b) 30 cm, c) 50 cm, d) 70 cm, e) 90 cm, f) 110 cm. Note that the irradiance scale changes significantly from image to image.



A benchmark for assessing whether the irradiance distribution's homogeneity on the surface is acceptable is the sensor's percentage accuracy [4]. According to the radiometer specifications, the accuracy is better than 6%, depending on parameters such as wavelength and integration time [2]. To assess whether the spatial variability in irradiance is significant in relation to the instrument's accuracy, we calculated the maximum Relative Deviation as a percentage. The definition of the Maximum Relative Deviation is (Equation 2):

$$MRD\% = 100 \cdot \frac{\text{Max}|E_i - E_a|}{E_a} \quad (2)$$

where:

- E_i is the irradiance of a generic element on the surface;
- E_a is the average irradiance across the entire surface.

In addition to $MRD\%$, we also report the standard deviation, but while $MRD\%$ highlights the single most deviant point relative to the mean, the standard deviation provides a measure of the overall dispersion of the irradiance values. In fact, the standard deviation can offer additional insight into the degree of homogeneity across the surface.

Figure 4 shows that the $MRD\%$ decreases rapidly with distance, falling below the spectrometer's nominal accuracy (better than 6%) at around 40 cm. Since the radiometer accuracy is better than 6%, the instrument can, in principle, distinguish irradiance variations of about 4-5%, depending on wavelength and measurement conditions. In our case, distances greater than 60 cm ensure an $MRD\% < 2\%$, providing a high degree of irradiance uniformity. Therefore, to further minimize residual gradients, the reflectance panel was placed at 80 cm from the light source. Furthermore, similar to the trend observed in the standard deviation, a significant reduction in $MRD\%$ in the first few tens of centimetres from the source is observed. Figure 4b illustrates this behaviour.

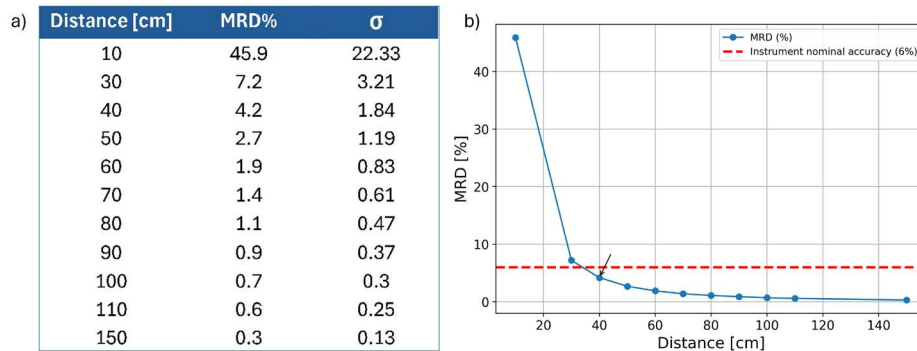


Figure 4 a) Table showing the standard deviation in percentage of the irradiance over the 14 cm x 14 cm panel and the $MRD\%$ as a function of the distance between the spherical source and the panel. **b)** Corresponding $MRD\%$ plot. The red line indicates the radiometer's nominal accuracy (6%).

2.2.2 Cylinder Source Shape

For a more detailed description of the phenomena, an additional simulation was conducted using a cylindrical source with a height of 3 mm and a base of 7 mm, which are the actual dimensions of the filament of the lamp. The characteristics of the source remain unchanged. This configuration is particularly useful for gaining a better understanding of the light distribution as the cylinder better approximates the emitting source with just the shape of its tungsten filament.

The results from Figures 4 and 5 are very similar, with slightly larger $MRD\%$ and standard deviation values for the cylindrical-shaped lamp. In this case, as well, distances larger than 40 cm between the source and the panel produce values of $MRD\%$ and σ smaller than the instrument accuracy. For the same reasons of the previous case, the chosen distance r source-panel was eventually set at 80 cm to maximize the irradiance homogeneity at the panel while maintaining the setup portability.

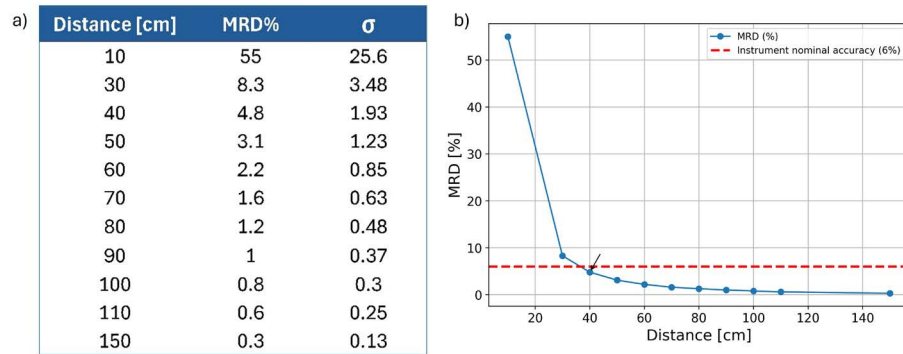


Figure 5 a) Table showing the standard deviation in percentage of the irradiance over the 14 cm x 14 cm panel and the $MRD\%$ as a function of the distance between the cylindrical source and the panel. b) Corresponding $MRD\%$ plot.

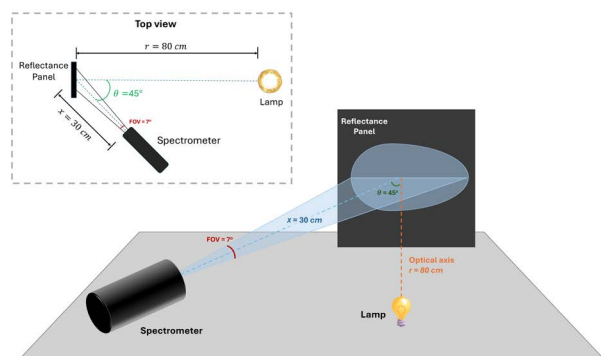
2.3 Spectrometer position and orientation

Regarding the distance between the spectrometer and the panel, as previously stated, it is essential that the light reflected by the homogeneously illuminated panel fills the sensor FOV. This requirement has been determined through simple trigonometric calculations, which indicate that the distance X , in our setup, must be less than 68 cm (Figure 6).

We decided to position the instrument at a distance of about 30 cm to ensure that small variations in the angle between the spectrometer axis and the main optical axis do not cause the FOV area of the spectrometer to exit the panel. It is important to note that the radiometer cannot be set too close to the panel because, at shorter distances, the presence of the sensor itself can distort the light reflected from the panel [Zibordi et al., 2019].

The angle between the instrument axis and the main optical axis is defined using a standard radiometer calibration practice based on optical and geometrical considerations to ensure accurate and reliable measurements. Using a 45° angle is consistent with industry standards and calibration procedures for radiance measurements and ensures repeatability and comparability between different instruments and measurement laboratories [Taubert et al., 2013].

Figure 6 The diagram shows the front view of the setup with the projection of the FOV area over the reflectance panel (in black for illustration purposes). The inset box provides a schematic view from above.



2.4 Calibration chamber setup

All the previously mentioned geometrical requirements are met, and the chamber setup is shown in Figure 7. The elements of the setup are positioned above the metal optical bench, which includes a grid of holes where the supports for the lamp, the panel, and the calibrating instrument are fixed. As previously mentioned, the baffles used are made of black cardboard. The first baffle, with a cylindrical shape, has a small hole to allow the passage of the light and it is used to isolate the lamp's light from the rest of the chamber. Furthermore, the open top of the cylinder allows heat to dissipate more effectively, resulting in less warming of the chamber. The second baffle, which is square-shaped, has a larger hole designed to further confine the light beam (Figure 7a). To avoid light contamination from the outside and ensure complete darkness during measurements, a chamber was built all around the optical bench, and an additional baffle was added to further control the light (Figure 7b). In addition to that, blackout fabric was used to line the inner walls and to reduce reflections (Figure 7c). The same blackout fabric was used as a lid to close the chamber and to prevent the external light from entering from the above. The chamber was equipped with a side opening to enable quick operations and adjustments during the measurements.

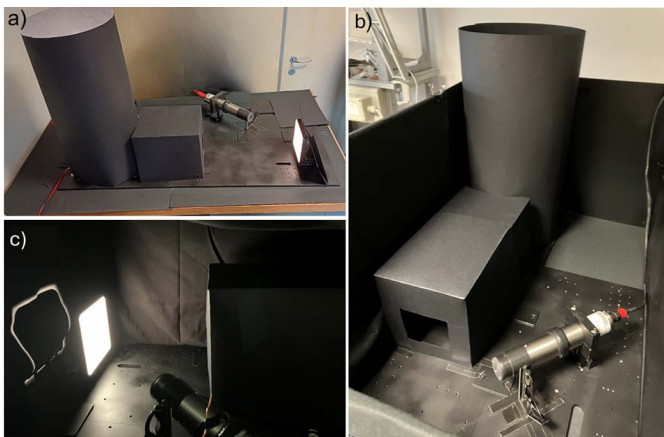


Figure 7 Different close-ups of the calibration chamber setup: **a)** setup elements with the Spectralon panel illuminated by the lamp; **b)** setup elements as seen from inside the chamber; **c)** internal chamber wall covered with the blackout fabric, with the panel illuminated.

3. Key Pre-Calibration Measurements and Corrections

Before proceeding with the spectrometer calibration, it is necessary to consider the integration time and take measurements to establish whether the setup is optimally designed to provide accurate measurements. This section shows how changes to specific settings and the positioning of the elements in the chamber setup affect signal collection.

3.1 Integration Times

To understand which integration time (t) should be chosen for the calibration, we created a graph showing the instrument calibrated signal measured with all the integration times (Figure 8). This figure shows that the shortest t (4 ms, in purple) produces a noisier signal; on the contrary, increasing t yields progressively smoother spectra. However, if the integration time is too long relative to the incoming radiance of the lamp, the detector saturates (see Figure 8 for integration times starting at 1024 ms and above). The largest t available in the instrument software which does not lead to saturation was chosen to reduce electronic noise; in our case, it is $t = 512$ ms. When saturation occurs, the raw counts hit the maximum and

radiance spectra are clipped when counts are normalized to the unit of time, i.e., the radiance $R(\lambda, t) / t$ decreases when the raw counts saturate and stays constant as t increases, as shown in Figure 8.

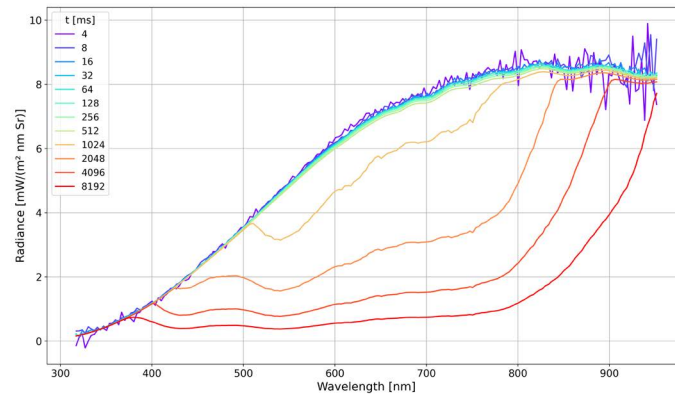


Figure 8 Plot of the measured lamp spectrum at all the integration times available for the RAMSES spectrometer. From measurements with an integration time of 1024 ms and above, the instrument sensor saturates and the power per unit time decreases as integration time increases.

3.2 Signal corrections

In order to calibrate the spectrometer, two important measurements need to be performed first: the dark signal and the ambient signal. The dark signal ($D(\lambda)$) is particularly important and it consists of two components: the background signal ($B(\lambda)$) and the electronic offset (EOF). $D(\lambda)$ represents the noise generated by the instrument in the absence of light incident on the sensor. It is measured with a cap on the instrument's aperture. $D(\lambda)$ helps to detect potential sensor drifts or anomalies caused by changes in the device's electronic behaviour [Zibordi et al., 2019]. $B(\lambda)$ acts as a fingerprint of the instrument, showing how one pixel 'sees' more light than another. It reflects pixel-to-pixel variations in the acquisition caused by imperfections in the electronic circuits or optical components. Ideally, it should remain stable over time, and it should be available from the manufacturer. Therefore, an analysis of this $B(\lambda)$ was carried out and compared with the original one; the details are provided in subsection 3.4, 'Dark signal'. The other important value is the electronic offset. It is an additional correction calculated by averaging the values of the last 18 dark pixels (specifically pixels 237–254) as detailed by the manufacturer. The EOF accounts for factors such as temperature changes during signal acquisition.

In contrast, the ambient signal ($A(\lambda)$) accounts for stray light or environmental radiation that can interfere with the calibrated source measurement. This signal depends on the setup configuration, and it may increase, for example, when external light enters the chamber and reaches the sensor, or when reflective surfaces inside the chamber contribute to unwanted scattering entering the spectrometer FOV. Therefore, we need to minimise $A(\lambda)$ in order to reduce systematic errors. If the $A(\lambda)$ is larger than the $D(\lambda)$, the setup should be improved [Zibordi et al., 2019]. To achieve this, the calibration system was enclosed and covered with black baffles and the light source was isolated from the RAMSES spectrometer. Once the setup achieved a significantly low level of $A(\lambda)$, we proceeded with taking accurate measurements of $A(\lambda)$. This was done by running the spectrometer while the calibrated lamp was on and while the baffle, the closest one to the reflectance panel, was kept shut, therefore blocking the direct path of the light between the source and the panel.

3.3 Setup sensitivity

In order to minimise $A(\lambda)$, we tested various setup configurations and shapes of the baffles, acquiring and comparing the various types until we arrived at the solution shown in Figure 7. This solution reduces diffused light and confines light more effectively to the surface of the panel. To understand the robustness of the setup, we introduced the following perturbations, analysing them one by one:

- baffle positioning;
- spectroradiometer orientation with respect to the main optical axis;
- spectroradiometer distance from the reflectance panel.

To evaluate the impact of these changes, we calculated the Percentage Residuals ($PR(\lambda)$), as defined in the Equation (3):

$$PR_{ref,pert}(\lambda) = \frac{L_{ref}(\lambda) - L_{pert}(\lambda)}{L_{ref}(\lambda)} \cdot 100 \quad (3)$$

where $L_{ref}(\lambda)$ represents the reference measurement and $L_{pert}(\lambda)$ the perturbed one. The variation of the position of the baffle is described below as an example to explain the $PR_{ref,pert}(\lambda)$ calculation.

First, we made 16 acquisitions ($N = 16$) with the light turned on in Position 0 (Figure 9a) and calculated their average value to reduce random noise and measurement uncertainty without excessively increasing the acquisition time, obtaining $S_0(\lambda)$.

Then, for the same reason, we took the same number of measurements of $A(\lambda)$, covering the hole of the baffle with a beam stop (Figure 9b), and took the average of these acquisitions to obtain $A_{m0}(\lambda)$. We then subtracted $A_{m0}(\lambda)$ value, from $S_0(\lambda)$ value and we obtained a measurement of the calibrated light source, which we called $L_0(\lambda)$, as shown in Equation (4):

$$L_0(\lambda) = S_0(\lambda) - A_{m0}(\lambda) \quad (4)$$

To understand the impact of changing the position of the baffle, we performed the same procedure for the Position 1 (Figure 9c) which is 6 cm away from the lamp and towards the panel (Figure 9d). Using Equation 4, we found $L_1(\lambda)$, which makes it possible to quantify the impact of the perturbation through Equation (3): $PR_{0,1}(\lambda) = [(L_0(\lambda) - L_1(\lambda)) / L_0(\lambda)] \cdot 100$, where $L_{ref}(\lambda) = L_0(\lambda)$ and $L_{pert}(\lambda) = L_1(\lambda)$.

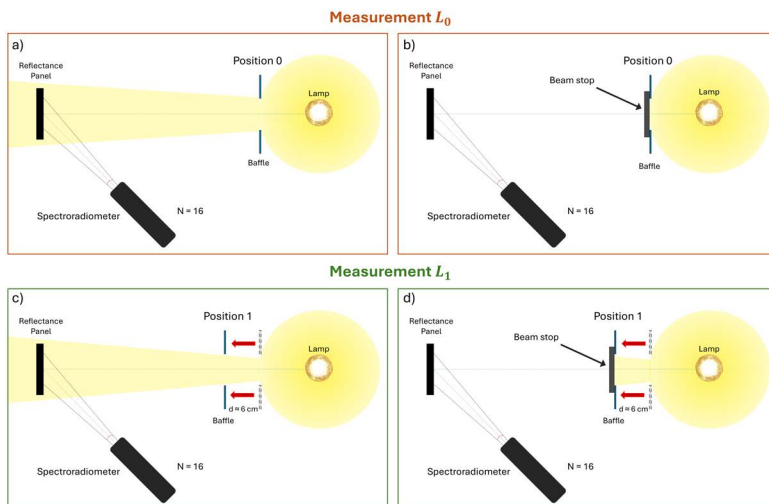
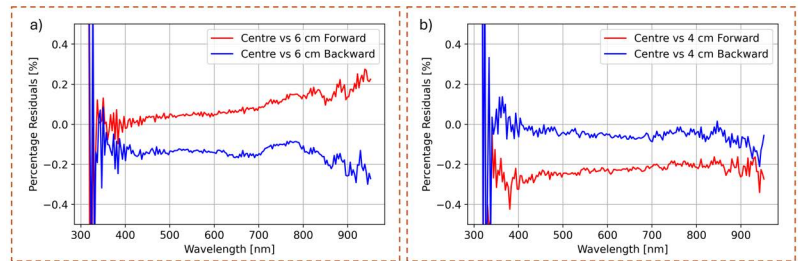


Figure 9 a) Scheme of the setup for the acquisition of $L_0(\lambda)$ (a), and **b)** the setup for acquiring the environmental signal with the beam stop for the baffle Position 0. Panels **c)** and **d)** show the same as a) and b) but with the baffle in Position 1 (the baffle is moved forward by 6 cm). $N = 16$ is the number of acquisitions made to obtain an average and more precise measurement. The view in each representation is from above.

Analogously, we also moved the baffle backwards towards the lamp by 6 cm with respect to Position 0 (named Position 2, not shown) and performed one more set of measurements ($L_2(\lambda)$) with and without the beam stopper in place. Figure 10a shows the obtained results, with the plot of $PR_{0,1}(\lambda)$ calculated using Equation (3), for Position 1 in red and the results for Position 2, $PR_{0,2}(\lambda)$ in blue, where the $L_{ref}(\lambda)$ is the same of $PR_{0,1}(\lambda)$ while $L_{pert}(\lambda)$ is the new measurement, $L_2(\lambda)$. Both perturbations affect the measured calibrated radiance $L_0(\lambda)$ by less than 0.4%. The second type of perturbation we considered concerns the distance between the spectrometer and the panel. The procedure is the same as that previously explained for variations in the baffle position. Considering the radiance measurement at the centre position of the spectrometer ($L_3(\lambda)$) and the radiance obtained when moving the spectrometer forward towards the panel by about 4 cm ($L_4(\lambda)$) (Figure 10b, red line), we calculated $PR_{3,5}(\lambda) = [(L_3(\lambda) - L_4(\lambda)) / L_3(\lambda)] \cdot 100$, according to Equation (3). The blue line in Figure 10b represents $PR_{3,5}(\lambda)$ obtained by displacing the spectrometer approximately 4 cm backward from the centre position, according to Equation (3). From Figure 10, it is evident that these two types of perturbation do not significantly affect the measurements.

Figure 10 The graphs show $PR_{ref,pert}(\lambda)$ for two types of perturbation: **a)** displacement of the baffle position forward and backward ($PR_{0,1}(\lambda)$ and $PR_{0,2}(\lambda)$), and **b)** displacement of the spectrometer position forward and backward ($PR_{3,4}(\lambda)$ and $PR_{3,5}(\lambda)$).



The third perturbation investigated was the variation of the spectrometer's angle with respect to the direction of 45° from the normal axis of the panel. $L_6(\lambda)$ is the radiance measured with an angle of $\theta = 45^\circ$ between the main optical axis of the system and the spectrometer's axis, while $L_7(\lambda)$ is the radiance measurement obtained with a variation of θ of approximately 1° . $PR_{6,7}(\lambda)$ is once again calculated following Equation (3). The results displayed in Figure 11b show a perturbation of less than 0.2% at almost all frequencies. Therefore, small errors in setting the spectrometer's direction do not result in significant variations in the acquired data. However, Figure 11a shows that the measured radiance decreases sharply (blue line) if the spectrometer FOV is not entirely filled with light coming from the Spectralon panel.

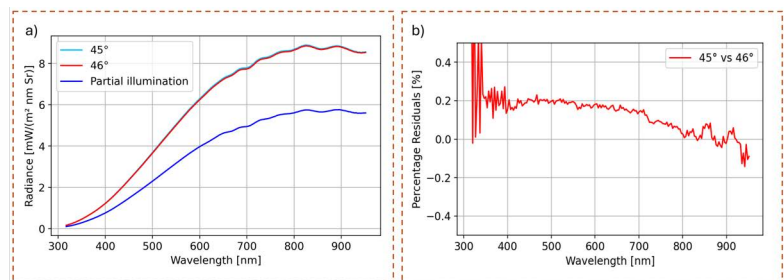


Figure 11 Perturbation of the spectrometer's pointing direction angle with respect to the main optical axis of the system: **a)** spectra corresponding to measurements carried out with the spectrometer at angles of 45° and 46° , and at an angle for which the spectrometer is only partially illuminated by the Spectralon panel and 'sees' also other elements of the chamber (indicated with "partial illumination" in the legend); **b)** $PR_{6,7}(\lambda)$ calculated for a 1° angle perturbation.

This is the most critical adjustment; once the position is set, it must be maintained consistently during the calibration process making sure that the entire area included in the FOV of the instrument is within the area of the Spectralon reflectance panel. Another important consideration is the angle of the panel, as this can affect the signal received by the spectrometer. It is important to ensure that the panel orientation does not change during calibration.

3.4 Dark signal

Having considered all possible variations in the setup, the next step is to evaluate any drift in the dark signal $D(\lambda) = B(\lambda) + EOF$ of our instrument. The background radiation $B(\lambda)$ is supplied by the data taking software together with the acquired radiance in the file BACK_SAM_xxxx.dat. The file contains two columns: B_0 and B_1 , and $B(\lambda)$ is calculated using the Equation (5):

$$B = B_0 + (t/t_0) \cdot B_1 \quad (5)$$

where t is the integration time (ranging from 4 ms to 8192 ms), and $t_0 = 8192$ ms is the normalization factor. In order to estimate an updated $B(\lambda)$ and compare it to the $B(\lambda)$ provided by the manufacturer, we took $D(\lambda)$ measurements by placing a cap on the optical input to the spectrometer. Following the manufacturer's manual [2], we then measured the EOF by averaging the values of the blackened pixels at the end of the diode array and removed EOF from the measured $D(\lambda)$. This was done for all integration times, and an average over 24 acquisitions was taken to obtain a reliable result, since dark current measurements are more sensitive to random noise (Figure 12).

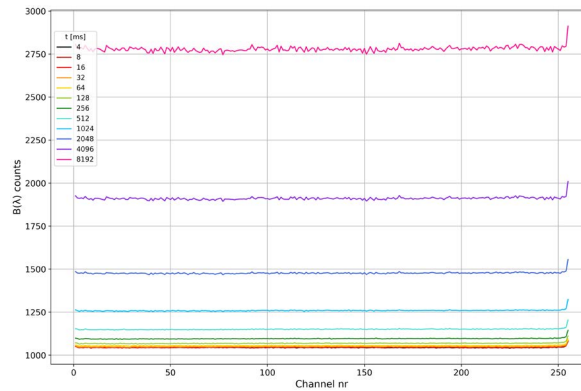
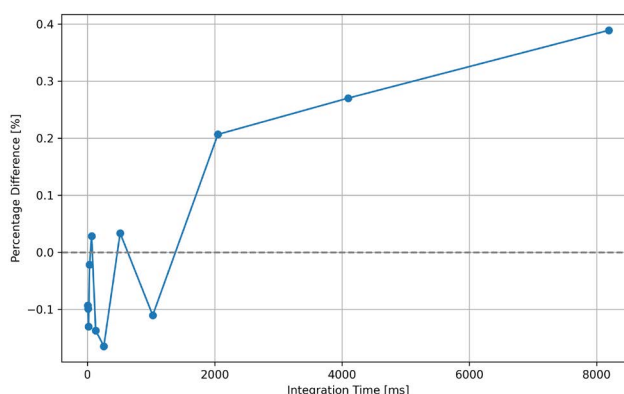


Figure 12 Background signal $B(\lambda)$ for all 12 integration times. Signals are averages over 24 acquisitions. The instrument operates at 16-bit resolution, corresponding to a maximum dynamic range of 65535 counts.

It is possible to compare the instrument's original fingerprint provided by the manufacturer in 2019 with the one obtained. The instrument preserves its linear behaviour for a single pixel and Figure 13 shows that the differences between our $B(\lambda)$ and the manufacturer's are very small, less than 0.4%. Therefore, this difference can be considered random, and the trend does not depend on the integration time. This analysis refers to a single pixel (pixel 122) across all integration times. The choice of pixel 122 is arbitrary and was made for illustrative purposes, and it corresponds to the wavelength of 713.1 nm.

Figure 13 Percentage difference, as a function of the integration time, between the new estimation of $B(122)$ (i.e., for pixel 122) and the original $B(122)$ provided by the manufacturer.



4. Calibration and spectra correction

In this section, we describe the overall procedure used to calibrate the spectrometer and the application of the correction function to the measured spectra.

4.1 Calibration procedure

Once the calibration setup had been characterized and optimized, we proceeded with the spectrometer calibration. Figure 14 summarises the most important steps of the procedure. In this section, we always refer to spectral irradiance and spectral radiance, but for convenience we will use the terms irradiance and radiance, respectively. It is important to note that the calibration correction function is independent of the integration time since it is normalized to the unit time. However, in this case, we selected an integration time of 512 ms.

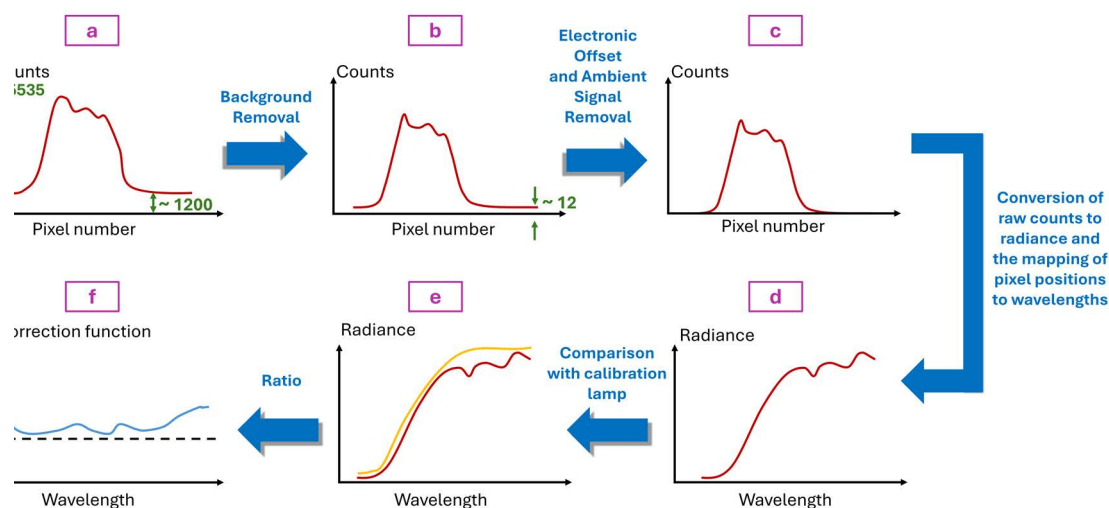


Figure 14 A schematic flowchart showing the data processing and the most important steps for the calibration procedure that leads to the correction function to apply to raw spectra. All the indicated values are for illustrative purposes only.

The calibration process is scheduled below:

1. The initial step is shown in Figure 14a where the spectrum of the raw data is represented, with pixel number on the x-axis and counts on the y-axis. The background $B(\lambda)$ is removed

from the raw data. This process can slightly alter the shape of the spectrum (Figure 14b). The electronic offset is then removed for an additional correction using the average of the dark pixel values, so there is no change in the shape of the spectrum.

2. Next, after having removed $B(\lambda)$ and its EOF from the ambient signal itself (as was done in the first step), this ambient signal is subtracted from the measurement (Figure 14c). This approach avoids double subtraction of $B(\lambda)$ and ensures that the EOF is properly removed from each measurement. We now have the corrected measurement, and it is possible to use a file provided by the manufacturer to convert counts to radiance. It is also important to convert the pixel number to wavelengths in order to obtain the correct spectrum. We therefore use the function provided by the manufacturer, which is given as a function of the pixel number ($N=1$ to 255). The function $\lambda(N+1)$ is fitted by polynomials of third order, Equation (6):

$$\lambda(N+1) = C_0 + C_1 \cdot (N+1) + C_2 \cdot (N+1)^2 + C_3 \cdot (N+1)^3 \quad (6)$$

where C_0 , C_1 , C_2 and C_3 are coefficients provided in the instrument specifications. The result is a spectrum with radiance on the y-axis and wavelengths on the x-axis (Figure 14d).

3. This newly found spectrum represents what the spectrometer observes when its FOV is filled with the calibrated lamp's light diffused by the Lambertian surface of the Spectralon panel. We then compare this spectrum to the calibrated spectrum provided by the lamp's manufacturer to obtain the correction function $Cf(\lambda)$ (Figure 14e, 14f). The manufacturer's specification for the calibrated irradiance spectrum is 50 cm from the source, and it is released in $W/(m^2 \cdot nm)$. The correct spectrum of the lamp is obtained through the following Equation (7):

$$E_r(\lambda) = E_{50}(\lambda) \left(\frac{50 + \Delta f}{r + \Delta f} \right)^2 \quad (7)$$

where E_{50} is the irradiance of the calibrated lamp at a distance of 50 cm as specified in the lamp's guidelines; Δf is the lamp's filament actual position with respect to the reference used in the specifications, namely the removable metal protective panel located in front of the lamp, and it is approximately 2 cm; r is fixed at 80 cm, as established in the previous section for the distance between the lamp and the panel, while the ratio $[(50 + \Delta f)/(r + \Delta f)]^2$ is the geometrical distance correction in order to determinate the irradiance at this actual distance between the lamp and the panel.

4. The lamp's irradiance must be converted to radiance and multiplied by the panel's reflectance efficiency values. As the reflectance characteristics of the panel are provided at different wavelengths with respect to the calibrated spectrum of the lamp, the panel's reflectance values, $\rho(\lambda)$, were first interpolated to match the lamp's wavelength spectrum. Then, for each wavelength, the radiance $L(\lambda)$ is obtained from the Equation (8):

$$L(\lambda) = \frac{\rho(\lambda)E(\lambda)}{\pi} \quad (8)$$

where L is the radiance and E the irradiance emitted by the lamp. If Ω is the solid angle ($\Omega = \sin(\theta)d\theta d\varphi$), the spectral irradiance is given by Equation (9):

$$E(\lambda) = \int_0^{2\pi} \int_0^{\pi/2} L(\lambda, \theta, \varphi) \cos(\theta) \sin(\theta) d\theta d\varphi \quad (9)$$

If the surface of the panel is Lambertian, $L(\lambda)$ does not depend on the angles θ and φ , and can therefore be extracted from the integral. Solving the two integrals, we'll find $E(\lambda) = L(\lambda) \cdot \pi$. In fact, in this case, the panel is a Lambertian surface, and it is therefore possible to simply divide E by π for the conversion to radiance (Figure 14e).

5. It is now possible to calculate the ratio between the calibrated spectrum measured by the RAMSES-ARC (based on the original manufacturer's calibration) and the updated calibrated lamp's spectrum, resulting in a $Cf(\lambda)$ that depends on wavelength (Figure 14f).

As explained in the next section, we use this $Cf(\lambda)$ to correct the spectra being acquired and saved by the spectrometer control software at the THAAO.

4.2 Application of the correction function to acquired data

A clear-sky case study acquired on 4th May 2022 at THAAO was analysed and is reported in Figure 15.

We compared the spectrum processed by the spectrometer using the factory calibration (Factory Calibrated Spectrum, shown in orange) with two additional spectra obtained by multiplying this factory-calibrated spectrum to evaluate the impact of the new calibration by two correction functions. The first $Cf(\lambda)$ was derived using a similar setup to the one discussed in this Technical Report but installed at the Laboratory of Atmospheric and Space Physics (LASP), University of Colorado in Boulder, USA, in 2022. The second was performed in 2025 at the INGV by using the setup described in this report. This approach allows to assess the effect of different calibration functions on the same dataset. The results are illustrated in Figure 15 and show a consistent change, which may be due to the ageing of the instrument or the different experimental setups used. The $Cf(\lambda)$ estimated in this work shows a potential trend in magnitude with respect to those from 2019 and 2022, which suggests the need for frequent calibration due to possible changes occurring over time.

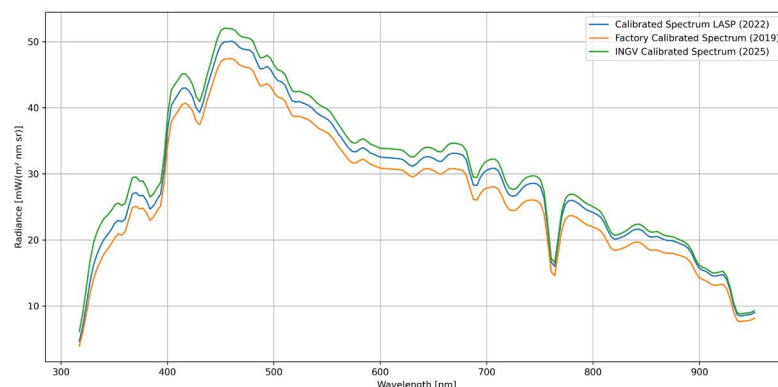


Figure 15 A factory-calibrated sky radiance observation in Greenland (4th May 2022 at 00:00:21) compared by applying different calibration functions: LASP calibration (LASP) and the most recent INGV calibration.

To better understand the behaviour of the $Cf(\lambda)$ as a function of wavelength, the correction functions obtained from the LASP (2022) and INGV (2025) calibrations, normalized to the factory calibration (set to 1), are plotted in Figure 16. These curves show the impact of the new calibrations on the spectral response, as well as the difference between the LASP and INGV calibrations.

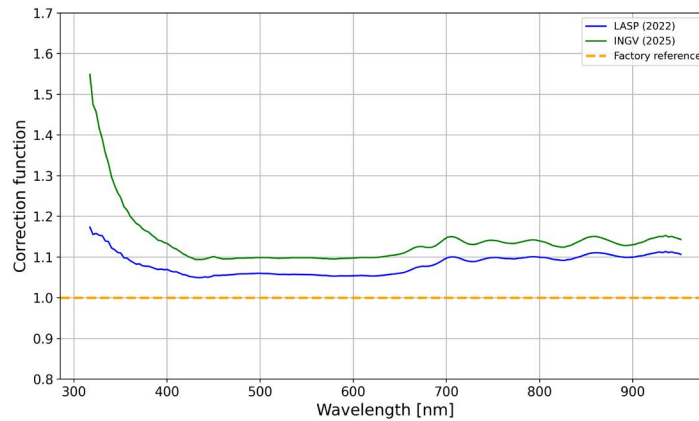


Figure 16 Comparison between the two spectral correction functions obtained from the ratio of INGV (2025) in green, and LASP (2022) in blue.

The frequency behaviour of these two $Cf(\lambda)$ values is very similar, with the exception of the first wavelengths (from 300 to 400 nm), where the curves are consistently larger than the reference line (Figure 16). This can be caused by several factors: the lamp radiance decreases strongly toward the UV-blue region, leading to a lower signal-to-noise ratio, when the signal is weak stray-light contributions become more significant; and both the optical components and the Si-based detector exhibit reduced responsivity in this range, which amplifies measurement uncertainty [Larason & Houston, 2008], [4]. Above 400 nm the two functions converge below 1.2, indicating that these effects are largely confined to the shortest wavelengths.

5. Conclusions and future steps

This report describes the calibration procedure developed at INGV for a RAMSES-ARC spectrometer manufactured by TriOS GmbH and operating in the UV-Vis-NIR spectral range. The setup guarantees repeatability and accuracy, and although not very small, it remains portable enough to be relocated if needed. The designed calibration procedure leads to the determination of a correction function to be applied to the spectral radiances saved by the acquisition software. Yearly calibrations will allow us to monitor potential changes occurring over time due to ageing and prolonged exposure of the spectrometer to harsh conditions. At this time we are unable to state whether the observed differences in the three calibration functions (Factory 2019, LASP 2022, and INGV 2025), resulting in the correction functions $Cf(\lambda)$ reported in Figure 16, are due to changes in the spectrometer characteristics with time or are due to the different setups employed for the three calibration processes; it's likely a combination of the both cases.

In the next few years, additional calibrations with the same chamber and setup designed at INGV and described in this work will allow us to better understand how the spectrometer characteristics are changing with time due to its operation in the harsh Arctic environment. For the moment, our approach is to consider valid each of the three calibrations and ascribe their differences to actual changes in the spectrometer characteristics. The RAMSES-ARC spectral radiances acquired at THAAO since August 2021 will therefore be calibrated employing the calibration that is the closest in time to the radiance measurements.

Future steps will aim at further improving the calibration procedure by understanding how temperature inside the chamber might affect calibration results. Additionally, this same setup

will be used to calibrate a second spectrometer that is under development at INGV and that will operate at THAAO observing the zenith radiance in the ShortWave IR spectral range (SWIR, 1-2.2 μm). The combination of the spectrometers will allow us to retrieve the cloud optical thickness, the effective radius and the phase (solid or liquid), providing important information on the relation between cloud characteristics and radiative fluxes at the surface.

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Ufficio Editoriale
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Segreteria di redazione
segreteria.collane-editoriali@ingv.it

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