International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

Traceable radiance source for spectroradiometer calibration

Steven van den Berg

Paul Dekker

Tessel van der Laan

Gerard Otter

et al.

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 1118068 · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536143

Traceable radiance source for spectroradiometer calibration

Steven van den Berg*[a], Paul Dekker[a], Tessel van der Laan[a], Gerard Otter[b], Niels Dijkhuizen[b],
Bilgehan Gür[b], Sanneke Brinkers[b]
[a]VSL, Thijsseweg 11, 2629 JA, Delft, The Netherlands;
[b]TNO, Stieltjesweg 1 , 2628 CK Delft, The Netherland

ABSTRACT

SI traceable calibration of satellite instruments like spectroradiometers get increasingly important in space-based observation for various reasons. First, requirements on measurements in terms of accuracy, dynamic range and wavelength range get increasingly demanding. Second, long term observations require SI traceability for comparability of data records that have been acquired over a long time interval (decades) and with different instruments. In this contribution we outline an approach for radiance calibration of spectroradiometers with a wavelength-tunable radiance source. The radiance source is based on an integrating sphere and a widely tunable laser (UVN-SWIR) and will be calibrated against a set of reference detector standards. By offering the radiance source as a stimulus to the spectroradiometer under test, the instrument can be calibrated for spectral radiance response. Potentially this traceability route could lead to a reduced measurement uncertainty compared to the traditional FEL-lamp based method. Furthermore, other instrument characteristics can also be derived from the same set of measurements, like stray-light effects and the instrument response function.

Keywords: Radiance measurement, detector calibration, metrology, traceability, Earth observation

1. INTRODUCTION

In today's world, satellite instruments are an essential source of vast amounts of information that is utilized not only in a wide field of scientific applications but also in our daily life. However, numerous technical aspects must be considered for proper operation and accurate interpretation of satellite data. Particularly, the physical quantities derived from satellites are of interest in atmospheric physics and geoscience. While on ground these physical quantities can be measured directly, this is not valid for space-based remote sensing. The satellite instrument detects the reflection or emission of radiation by the Earth's surface or atmosphere, which then allows the retrieval of associated physical quantities. As the basic physical principle is set by the interaction of radiation with the earth's atmosphere and surface (radiative transfer), the use of radiances and their respective units are preferred within retrieval methods accordingly.

Current state of the art for radiance response calibration is the use of a FEL lamp with diffuser or a calibrated integrating sphere. The advantage of these sources is their broad band (white light) output, so that the entire spectral range can be illuminated at once. The disadvantage of these sources is that they illuminate far more than desired in the sense of geometry and spectral range. Therefore, additional measurements are required with specialized sources to further characterize the instrument. In this paper we present an alternative approach, which is currently under development. Here a tunable radiance source based on a laser, merges the radiance calibration of a satellite instrument and its characterization of spectral effects (instrument response function measurements and stray light characterization) in a single measurement. This reduces the overall calibration time of the instrument. The instrument calibration method is discussed in section 2. As discussed in section 3, the source consists of a widely-tunable pulsed laser that is fed into an integrating sphere. The flux within the sphere will be measured continuously with a monitor detector to monitor the stability of the source. To keep measurement time as short as possible, the source needs to be powerful with a spectral output power close to the maximum earth radiance expected for these kinds of instruments. The radiance source will be calibrated by measuring the flux with a calibrated reference detector, through a well-defined aperture at the detector, as described in section 4. The transfer of the flux from the radiance source to the detector is determined by the geometry of the system. The calibration of the source radiance is performed as a function of wavelength. For each set wavelength, the radiance emitted from the source aperture is measured with a calibrated reference detector. Different types of calibrated reference detectors will be used to cover the complete

---

* svdberg@vsl.nl

wavelength range (270 nm – 2400 nm). All reference detectors will be calibrated against an absolute cryogenic radiometer, which is VSL's national primary standard for responsivity calibration. In section 5 a preliminary uncertainty budget is discussed, followed by a conclusion and a short discussion on case validation in section 6.

2. MEASUREMENT METHOD FOR INSTRUMENT RADIANCE CALIBRATION

The necessity for a thorough radiometric calibration of a sensor or an earth observation instrument before its placement into orbit is manifold. In this so-called pre-launch or on-ground calibration process tests are performed in a controlled environment with known sources to verify proper instrument operation, evaluate and quantify sensor characteristics etc. Since the primary unit of a sensor consists of digital counts, calibration has to be applied in order to relate these counts or binary units to physical units of interest, e.g. such as sun irradiance or earth radiance levels. For this purpose, various calibration sources are used to provide well-known and repeatable flux levels as optical input to the sensor being calibrated. These sources are provided by metrology organizations that can provide traceability to primary radiometric standards. In this section we will describe two setups, the calibration measurements with a FEL lamp and the novel method with the calibrated refence detector.

2.1 FEL lamp-based radiance source

For absolute radiance calibration measurements, a calibrated FEL lamp will be used. To convert the lamp irradiance into a radiance a diffuser is used. This diffuser BRDF (bidirectional reflectance distribution function) needs to be calibrated as well. Since the FEL lamp will change due to the evaporation of the tungsten coil over time, the time the lamp calibration is valid is limited. So, for extensive measurements at e.g. different geometrical configuration this setup is less suitable. For these relative measurements can be used with an integrating sphere. The graphics below display a basic schematic view of a usual FEL setup:

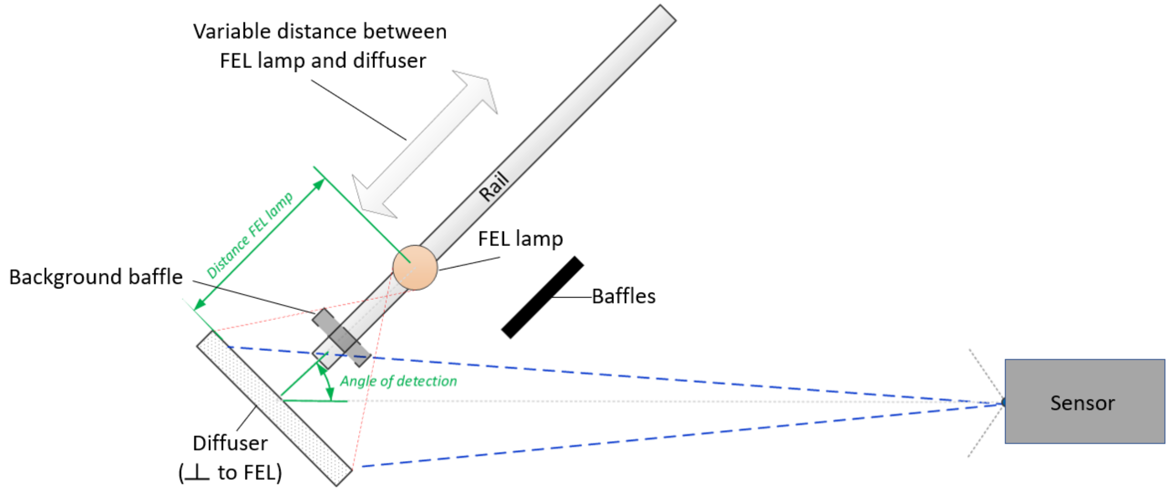


Figure 1. Basic schematic display of instrument radiance calibration approach with a FEL lamp

A FEL lamp is mounted on a rail illuminating a calibrated OGSE (Optical Ground Support Equipment) diffuser. This is to convert the FEL lamp as an irradiance source into a radiance source. The distance between the FEL lamp and diffuser is variable and measurements will usually be performed at 3 or more different positions to identify potential alignment errors and changing background levels. Ideally the diffuser is oriented perpendicular to the FEL lamp as indicated above.

In this configuration a symmetrical radiance distribution on the sensor footprint of the diffuser can be realized, which makes it less sensitive to alignment errors. The uncertainty budget for such a setup is discussed in section 5.

2.2 Laser-based radiance source

An integrating sphere provides the possibility to generate very homogeneous radiance levels. If used with QTH (quartz tungsten halogen) lamps and radiometrically calibrated, this would provide a nice radiance source but with the same limitations as the FEL with respect to the time the calibration is valid. Therefore, a different method is foreseen [1]. The integrating sphere will be provided with a tunable monochromatic source (laser) and a monitor detector. This configuration will be completely calibrated and the calibration is effectively transferred to the monitor detector. A schematic setup is shown in Figure 2 below. The monitor detector can be a single pyro electric detector if the signal level is sufficient or a combination of Si-detector for the ultra violet (UV) up to near infrared (NIR) wavelengths with an enhanced InGaAs, PbS or MCT detector in the short-wave infrared (SWIR).

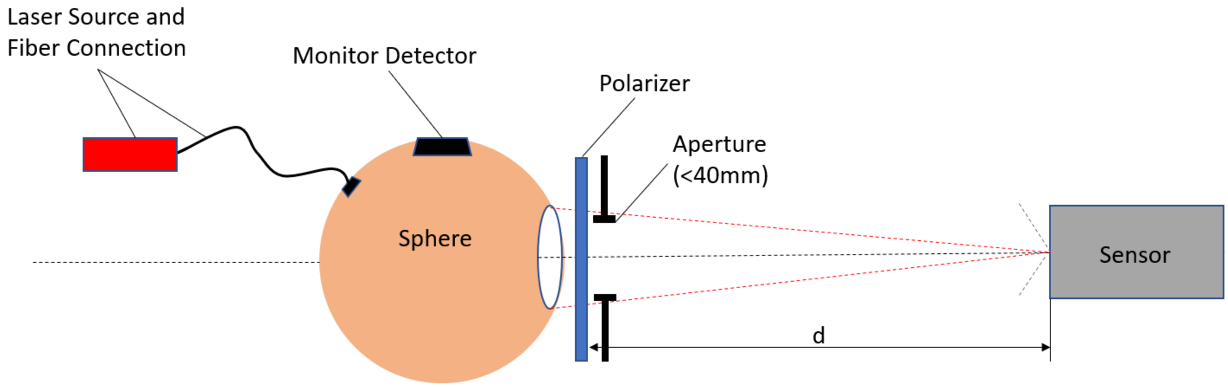


Figure 2. Basic schematic display of instrument radiance calibration approach with an integrating sphere

A monochromatic source illuminates via a fiber connection the inside of a calibrated sphere. These spheres are commercially available and are coated inside with a diffusing material, ensuring very homogeneous radiance levels. The sphere is aligned with the according sensor or instrument, which views the generated radiance. Several aspects need to be considered in the design of such a setup, such as a sufficient size of the sphere and sphere exit, in particular with respect to the instruments pupil size and field of view. Additionally, a polarizer can be added for calibrated polarization measurements.

The whole system needs to be calibrated for absolute radiance output. For that a physical stop is added in front of the system to create a clear reference aperture. Since the sphere will de-polarize the input, the output of the sphere is un-polarized and the radiance after the polarizer will be independent of the polarization direction. For polarization measurements it must be considered that the polarizer will not be perfect. The Stokes vector of the system must therefore also be determined. This can be done with relative measurements.

3. RADIANCE SOURCE DESIGN

As described before, it is foreseen to use an integrating sphere with a monochromatic source, i.e. a laser. In principle any monochromatic source can be used as input. On our case we use a tunable laser available at TNO. This is the EKSPLA NT242 PGD11 laser system. It has in a single compact housing a diode pumped Q-switched laser which pumps an optical parametric oscillator system offering hands-free, no-gap tuning from 210 to 2500 nm. It offers nanosecond pulses at 1000 Hz repetition rate. The integrating sphere that will be used is a 12” sphere with 4” opening. Based on these values and the laser output as specified by the manufacturer, the expected radiance levels have been calculated. Figure 3 shows a comparison between the typical earth radiance levels and the achievable radiance with the laser-based system. In many cases the source output is higher than the maximum radiance. This gives a convenient margin but also the danger that the instrument will be saturated, which can be overcome by using neutral density filters.

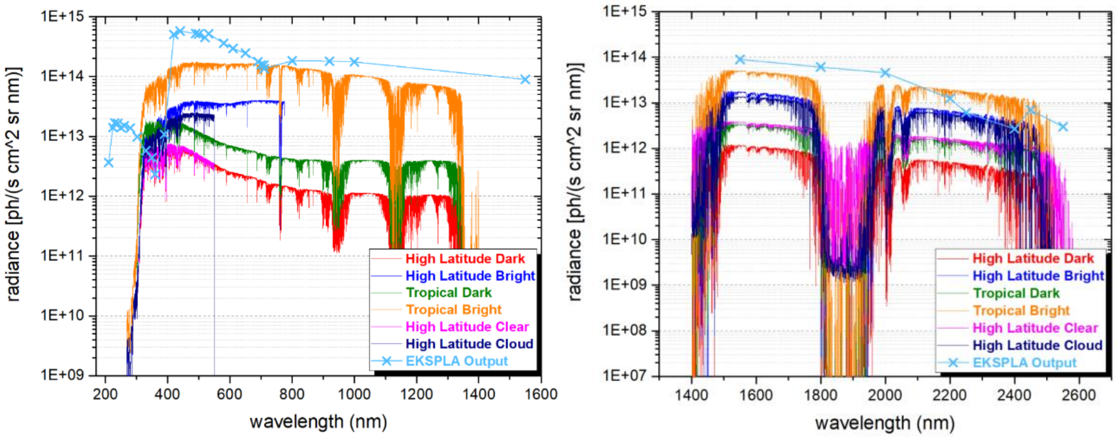
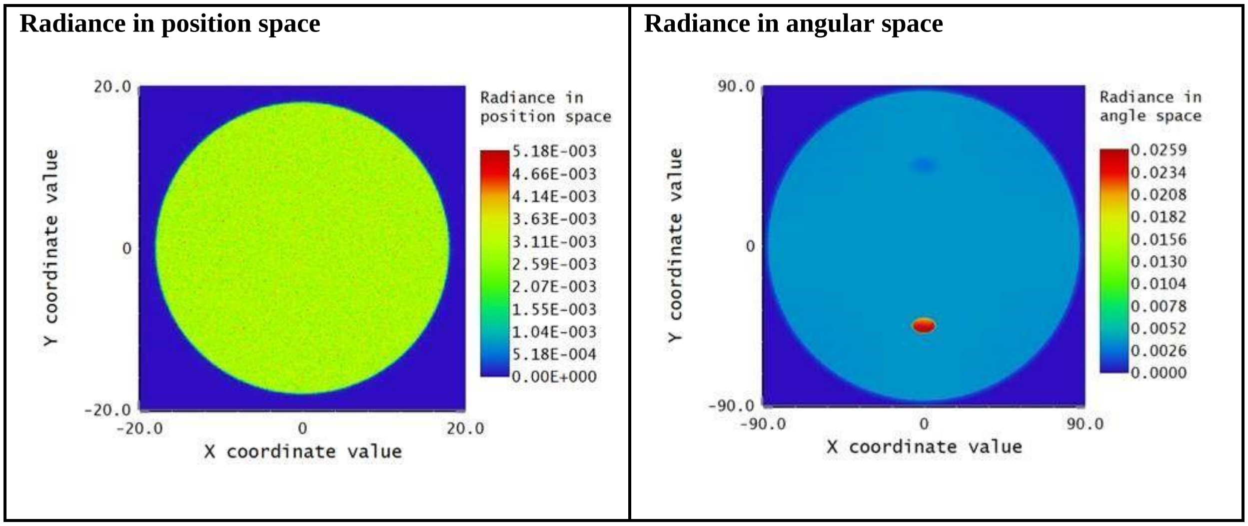


Figure 3. Comparison of radiance levels and EKSPLA output in the UVN range (left) and SWIR range (right)

The integrating sphere will give a very homogenous radiance in the spatial domain but will not be completely homogenous in the angular domain. For perfect Lambertian scatter the characteristics are similar to the images below (Figure 4) based on a ZEMAX model of an integrating sphere. The hot spots in the angle space are due to the source illumination (i.e. the laser beam) but are way outside the angular range of interest. The diffusing material will not be perfect Lambertian, so a slight increase in inhomogeneity is expected. For this radiometric calibration the sphere area used shall be in the homogeneous part. The sphere area used depends on the pupil size and the field of view used in the instrument calibration. This shall also be considered for the source calibration setup. Both the calibration setup and the instrument to be calibrated should only be able to view the homogenous part of the sphere. Typical only a few degrees of field should be considered, which is sufficient for instrument calibration.


Radiance in position space

Radiance in angular space

Figure 4. ZEMAX model of the beam homogeneity of an integrating sphere

4. SI TRACEABLE RADIANCE SOURCE CALIBRATION

The radiance source will be calibrated by measuring the flux with a calibrated reference detector, through a well-defined aperture at the detector. The calibration setup is shown in Figure 5. The transfer of the flux from the radiance source to the detector is determined by the geometry of the system: the radius of the source aperture R_s, the radius of the detector aperture R_d, and the distance d between both apertures. Light from a pulsed laser source (Optical Parametric Oscillator, OPO) as described above, is fed into the integrating sphere via a fiber port. The flux within the sphere is measured with a monitor detector. The aim of the calibration is to link the monitor detector reading to a known radiance level from the source aperture, providing traceability of the integrating sphere radiance source to the SI.

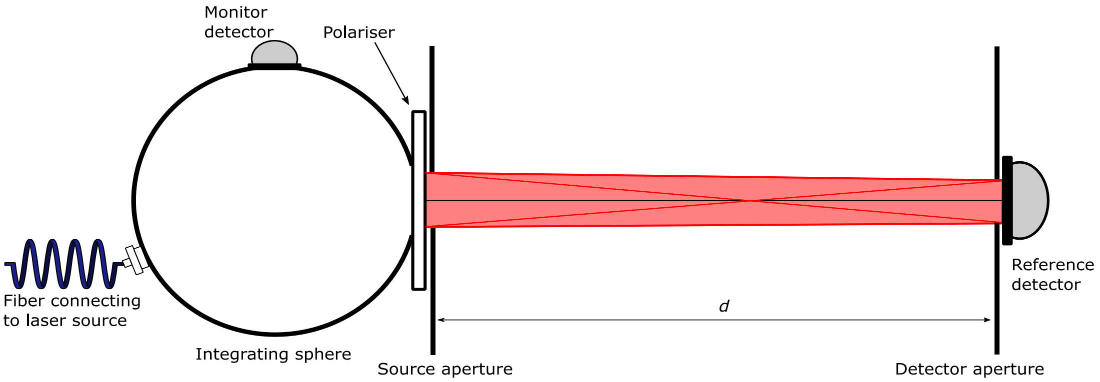


Figure 5. Schematic overview of the calibration setup for radiance calibration

The calibration of the source radiance is performed as a function of wavelength, by tuning the OPO source wavelength. For each set wavelength, the radiance emitted from the source aperture is measured with the calibrated reference detector. The absolute radiance level is determined from the measurement geometry and the calibrated absolute spectral response of the reference detector at the set wavelength of the source. Both the reference detector and the monitor detector are read simultaneously with a gate time that is set such that pulse-to-pulse fluctuations from the OPO source are averaged out to a negligible level.

Different types of calibrated reference detectors will be used to cover the complete wavelength range. A Si trap detector, Ge (or InGaAs) detector and an (extended) InGaAs-based detector will serve as reference detectors covering the VNIR and SWIR wavelength range. All reference detectors will be calibrated against an absolute cryogenic radiometer, which is VSL’s national primary standard for detectors responsivity calibration. The measurement uncertainty on the detector responsivity calibration varies with wavelength and is discussed in section 5. The calibration requires both responsivity calibration of the reference detectors and geometrical calibration of the precision apertures that are in front of the source and the detector. The calibration of the apertures will take place with a coordinate measurement machine (CMM). The CMM is traceable to the SI meter via a calibrated laser reference. Figure 6 shows the traceability chain of source radiance calibration to primary standards.

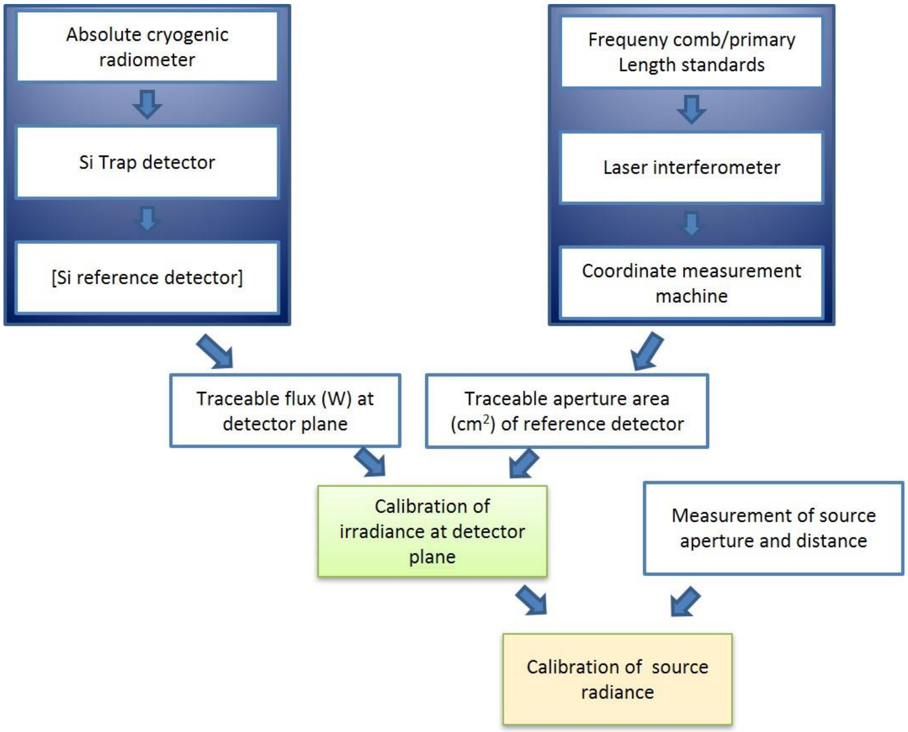


Figure 6 Traceability chain of source radiance calibration

5. PRELIMINARY UNCERTAINTY BUDGET

In this section the preliminary uncertainty budget on radiance calibration is discussed. Here, assumptions on measurement accuracy and signal to noise ratio need to be made. These estimated values need to be replaced by the measured values once the calibration has been performed.

The amount of flux Φ received by the aperture of the reference detector is given by:

$$\Phi = L(\lambda)\pi^2 R_s^2 f, \tag{1}$$

with R_s the source diameter and L the radiance emitted from the source at wavelength λ. A fraction of the flux emitted by the source reaches the detector. This fraction, f, depends on source and detector radius, R_s and $R_{d,}$ and the distance between source and detector, d [2]:

$$f = 2\frac{R_d^2}{(R_s^2 + R_d^2 + d^2) + \sqrt{((R_s^2 + R_d^2 + d^2)^2 - R_s^2 R_d^2)}} \tag{2}$$

For a continuous wave source, typically a transimpedance amplifier is used to measure the photocurrent, providing an output signal V:

$$V = \mathrm{G}\Phi\mathrm{R}(\lambda), \tag{3}$$

with G, the gain of the amplifier, and $\mathrm{R}(\lambda)$ the responsivity of the detector. The average radiance from the source is given by:

$$\mathrm{L}(\lambda) = \frac{\mathrm{V_l} - \mathrm{V_d}}{\mathrm{G} \cdot \mathrm{R}(\lambda)} \frac{1}{\pi^2 \, \mathrm{R_s}^2 \mathrm{f}} \tag{4}$$

Here, $\mathrm{V} = \mathrm{V_l} - \mathrm{V_d}$, the voltage difference between measurement with illumination and the dark measurement. For pulsed sources, several options for measuring the photocurrent can be chosen, e.g. based on a gated integrator, a charge meter or by using a low-bandwidth transimpedance amplifier. This will be further investigated and will lead to an ‘effective gain’ G, which depends on the selected detection method.

5.1 Uncertainty on source calibration

Based on equation (4), the uncertainty on the calibration of the radiance source is determined. The uncertainty consists of contributions come from geometrical measurements and optical measurements. The standard uncertainty on the radius calibration with the CMM is estimated to be 2 µm, depending on the quality of the roundness of the aperture. The standard uncertainty on the distance measurement d is estimated to be 0,1 mm for manual positioning with a calliper gauge. The uncertainty on the distance between aperture and reference plane with the CMM is estimated to be negligible compared to this calliper gauge measurement.

The measurement uncertainty on $\mathrm{V_l}$, $\mathrm{V_d}$ and G consists of several components and strongly depends on the signal level. The measurement uncertainty of the reference detector responsivity is strongly wavelength dependent, ranging from $<$ 0.1% in the visible to $>$ 1% in SWIR. An example uncertainty budget for 300 nm is shown in Table 1.

Table 1 Preliminary uncertainty budget of radiance source calibration at 300 nm

Input variable	Std. uncertainty on input variable (%)	Sensitivity coefficient	Contribution to std. uncertainty on radiance calibration (%)	Remarks
$\boldsymbol{R(\lambda)}$	0.25	1	0.25	@300 nm
$\boldsymbol{R_s}$	0.016	2	0.032	
$\boldsymbol{R_d}$	0.067	2	0.13	
d	0.025	2	0.050	
Alignment	0.1	1	0.1	Estimate, to be determined experimentally
SNR	0.61	1	0.61	At estimated radiance level of 0.1 W/m2/sr Includes uncertainty on V_l, V_d, G
Pulsed detection	0.2	1	0.2	Estimate, to be determined experimentally.
Combined Uncertainty			**0.7 (k=1)**	

5.2 Uncertainty on instrument calibration

The uncertainty budget for the calibration of a spectroradiometer using the FEL lamp-based method as described in section 2 is summarized in the table below. The use of the diffuser to convert irradiance to radiance gives rise to several substantial uncertainty contributions.

Table 2 Uncertainty budget of the calibration of a spectroradiometer instrument with at FEL lamp at 300 nm

Uncertainty Contribution	Estimated std. uncertainty contribution 300 nm (%)	Remarks
Light source calibration accuracy	0.9	Typical FEL lamp calibration accuracy at 300 nm
Diffuser calibration	0.7	BRDF calibration accuracy
Alignment FEL – Diffuser	0.4	This uncertainty is based on the geometric uncertainties expected in the setup including the lamp optical centre knowledge. The value is for a single FEL distance.
Alignment diffuser – Instrument	0.1	
Non-infinite instrument footprint	0.11	The distance between FEL lamp and diffuser is considered the distance of the centre of the diffuser and the lamp. Off centre on the diffuser the distance will increase. Because the instrument will view an area on the diffuser this area will be illuminated inhomogeneous, which contributes to the measurement uncertainty.
Measurement noise	0.1	This is basically the signal-to-noise of the measurement, which is assumed to be 1000.
Combined uncertainty	**1.2**	

Similarly, a preliminary uncertainty budget for the laser-based setup has been created. Here, several contributions related to the diffuser disappear. Note that all contributions are currently estimations, they will need to be determined experimentally.

Table 3 Preliminary uncertainty budget of the calibration of a spectroradiometer instrument with a calibrated laser-based radiance source at 300 nm.

Uncertainty Contribution	Estimated std. uncertainty contribution 300 nm (%)	Remarks
Light source calibration accuracy	0.7	For now, it is set equal to the FEL. This number will be replaced by the uncertainty on the calibration of the radiance source.
Monitor detector noise	0.1	Assumed signal-to-noise of the monitoring detector is 1000.
Alignment Sphere – Instrument	0.1	This uncertainty is small because the sphere has no strong spatial and angular dependence.
Measurement noise	0.1	This is basically the signal-to-noise of the measurement, which is assumed to be 1000.
Combined uncertainty	**0.72**	Preliminary value at 300 nm

6. CONCLUSION AND OUTLOOK

We have described a calibration method for traceable radiance calibration of spectroradiometers, based on a tunable laser source. Compared to traditional FEL lamp calibration this method offers several advantages. Spectroradiometers can be directly calibrated as a function of wavelength by tuning the radiance source. This does not only provide the radiance calibration, but also provides information on instrument response function and stray light effects from a single wavelength scan. This is an advantage compared to traditional FEL lamp calibration, which requires additional (relative) measurements to characterize these parameters. Currently, the measurement setup is under construction. As a case validation the calibration of a spectroradiometer in the visible range will be performed, comparing the FEL lamp method and the tunable laser method. The spectroradiometer under test will be the TROPOLITE breadboard model[3]. The TROPOLITE is an instrument, designed to fly on a cube-sat, focusing on NO_2 detection and has a spectral range of 300 to 500nm with a resolution of about 0.5 nm. The instrument slit is dispersed in one direction and imaged in the other direction. From both setups an absolute radiance calibration of the TROPOLITE bread board will be obtained. These should give the same results within the uncertainty budgets. The potential differences between the measurements will be evaluated considering the different uncertainty contributors.

ACKNOWLEDGEMENTS

This work was funded by the European Metrology Programme for Innovation and Research (EMPIR), Project 16ENV03, MetEOC-3, ‘Further metrology for Earth Observation and Climate’. EMPIR is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States.

REFERENCES

[1] Zong,Y., Brown, S. W., Eppeldauer, G. P., Lykke, K. R. and Ohno, Y, “A new method for spectral irradiance and radiance responsivity calibrations using kilohertz pulsed tunable optical parametric oscillators”, Metrologia 49, S124-S129 (2012).

[2] Gaertner, A. A., [Optical Radiation Measurement], Modern Metrology Concerns, Luigi Cocco (Ed.), InTech, DOI: 10.5772/35476. Available from: https://www.intechopen.com/books/modern-metrology-concerns/optical-radiation-measurements (2012).

[3] De Goeij, B. T. G., Otter, G.C.J., Van Wakeren, J.M.O., Veefkind, J.P., Vlemmix, T., Levelt, P.F., Dirks, B.P.F. Toet, P.M., Van der Wal, L.F. and Jansen, R., “First aircraft test results of a compact, low cost hyperspectral imager for earth obvervation from space”, International Conference on Space Optics — ICSO 2016, Proc. SPIE, 10562N (2017).