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Providing Radiometric Traceability for the Calibration Home Base of DLR by PTB

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Abstract. A dedicated calibration technique was applied for the calibration of the spectral radiance transfer standard (RASTA) of the German Aerospace Center (DLR) at the Physikalisch-Technische Bundesanstalt (PTB), consisting of two independent but complementing calibration procedures to provide redundancy and smallest possible calibration uncertainties. Procedure I included two calibration steps: In a first step the optical radiation source of RASTA, an FEL lamp, was calibrated in terms of its spectral irradiance $E_\lambda(\lambda)$ in the wavelength range from 350 nm to 2400 nm using the PTB Spectral Irradiance Calibration Equipment (SPICE), while in a second step the spectral radiance factor $\beta_{0^\circ:45^\circ}(\lambda)$ of the RASTA reflection standard was calibrated in a $0^\circ:45^\circ$ - viewing geometry in the wavelength range from 350 nm to 1700 nm at the robot-based gonireflectometer facility of PTB. The achieved relative standard uncertainties ($k = 1$) range from 0.6 % to 3.2 % and 0.1 % to 0.6 % respectively. Procedure II was completely independent from procedure I and allowed to cover the entire spectral range of RASTA from 350 nm to 2500 nm. In the second procedure, the $0^\circ:45^\circ$ -viewing geometry spectral radiance $L_{\lambda,0^\circ:45^\circ}(\lambda)$ of RASTA was directly calibrated at the Spectral Radiance Comparator Facility (SRCF) of PTB. The relative uncertainties for this calibration procedure range from 0.8 % in the visible up to 7.5 % at 2500 nm ($k = 1$). In the overlapping spectral range of both calibration procedures the calculated spectral radiance $L_{\lambda,0^\circ:45^\circ,\text{calc}}(\lambda)$ from procedure I is in good agreement with the direct measurement of procedure II, i.e. well within the combined expanded uncertainties ($k = 2$) of both procedures.

Keywords: Calibration, Metrology, Radiometry, Reflectometry, Spectral irradiance, Spectral radiance factor, Spectral radiance, Radiance standard, Standards.

PACS: 01.52.+r, 06.20.fb, 07.60.-j, 42.72.Bj

INTRODUCTION

The German Aerospace Center (DLR) has developed a new radiance standard (RASTA) [1] which is used since 2012 as reference for absolute radiometric measurements in the DLR calibration facility for airborne imaging spectrometers [2]. To fulfill the radiometric traceability requirements, a dedicated calibration technique was developed and applied at the PTB for RASTA consisting of two complementing procedures. *Procedure I* consisted of two adjacent calibration steps: In a first step the radiation source of RASTA, an FEL lamp, was calibrated in terms of its spectral irradiance $E_\lambda(\lambda)$, while in a second step the spectral radiance factor $\beta_{0^\circ:45^\circ}(\lambda)$ of the reflection standard of RASTA was calibrated in a $0^\circ:45^\circ$ - viewing geometry. Both calibration steps then allow the calculation of the spectral radiance $L_{\lambda,0^\circ:45^\circ,\text{calc}}(\lambda)$ of RASTA for a given condition of illumination and alignment geometry according to:

$$L_{\lambda,0^\circ:45^\circ,\text{calc}}(\lambda) = \frac{E_\lambda(\lambda) \cdot \beta_{0^\circ:45^\circ}(\lambda)}{\pi} \quad (1)$$

In the second procedure (*Procedure II*) the spectral radiance $L_{\lambda,0^\circ:45^\circ}(\lambda)$ for the $0^\circ:45^\circ$ - viewing geometry of RASTA was calibrated directly, this procedure being completely independent from *Procedure I*.

DLR'S RADIANCE STANDARD RASTA

The mechanical configuration of RASTA is shown in Figure 1. Light source is a 1000 Watt FEL tungsten halogen lamp. It illuminates perpendicularly a reflectance panel with the dimension 25 x 25 cm² (1). To minimize stray light contamination, the lamp is installed inside a lamp housing (2). The lamp housing is mounted on a

translation stage (3) to allow well-defined intensity changes by altering the distance between lamp and panel. A mounting adapter (4) provides space for seven instruments, which are arranged on a half circle around the panel center. This set-up ensures that the optical axis of each instrument intersects the panel center at an angle of 45°, thus minimizing errors caused by spatial or angular inhomogeneities. Five of the adapter fittings are used for radiometers (5,6) which monitor redundantly the stability of the system. The two remaining fittings on bottom left and right (7) are used for the instruments which shall be calibrated. Large or heavy sensors can be placed adjacent to the system using separate mounts.

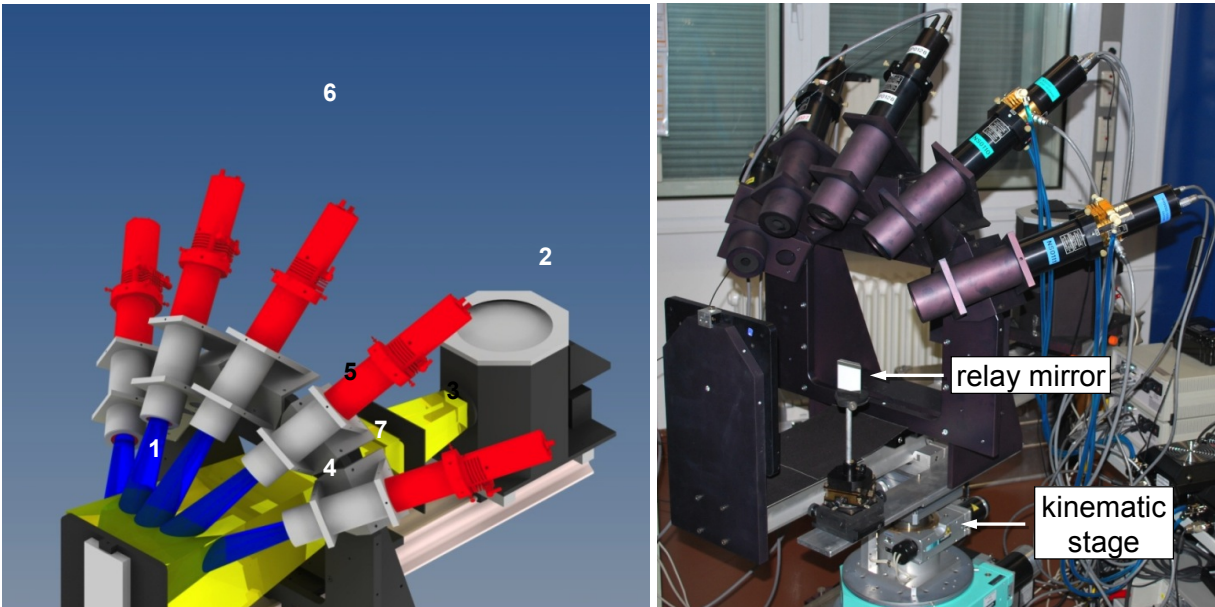


FIGURE 1. Mechanical set-up of RASTA (left): (1) Reflectance panel, (2) lamp housing, (3) translation stage, (4) mounting adapter, (5) radiometer holder, (6) radiometer, (7) sensor fitting. Yellow: beam illuminating reflectance panel, blue: field of view of radiometers. RASTA after its alignment for calibration in the 0°:45° viewing geometry at the SRCF of PTB (right).

PROCEDURE I

Calibration of the Spectral Irradiance $E_{\lambda}(\lambda)$

At PTB, the realization of the spectral irradiance is based on a black-body radiator as the national primary standard [3]. When the radiator temperature, the effective emissivity and the measurement geometry of the radiator are exactly known, the spectral irradiance can be realized in accordance with Planck's radiation law. With the aid of a high-precision spectroradiometer, different radiators are calibrated as secondary standards against the black-body radiator. The facility in question is a double monochromator system with an integrating sphere as entrance optics [4]. The aperture of the sphere serves as the reference plane. With three grating pairs and different detectors in use, the spectroradiometer can cover a spectral range from 220 nm to 2400 nm. At PTB, 1000 W quartz tungsten-halogen lamps of the type FEL – which are directly calibrated against the primary standard at regular intervals – are used as secondary standards. The RASTA radiant sources which are operated in an air-conditioned lamp housing were calibrated against a group of these secondary standards. The 1000 W FEL radiant sources in the housing were measured at a distance of 1000 mm to the reference plane of the spectroradiometer, in accordance with the RASTA measuring set-up. The remaining set-up (filter radiometer supports and Spectralon® reflection standard) was not used here.

The measurement procedure is in compliance with the traceability chain used at PTB for customer calibrations [5]. The relative standard measurement uncertainties of this calibration lie between 0.6 % in the visible spectral range and 3.2 % at 2400 nm ($k = 1$). The measured spectral irradiance and the associated standard measurement uncertainty are shown in Figure 2(a).

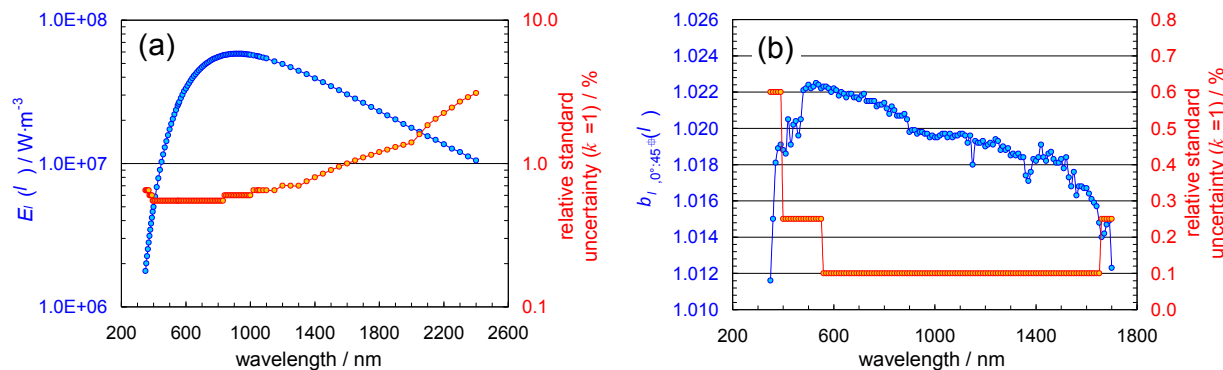


FIGURE 2. The spectral irradiance $E_l(\lambda)$ of a 1000 W FEL quartz halogen lamp applied as the radiation source of RASTA (a) and the spectral radiance factor $\beta_{l,0^\circ:45^\circ}(\lambda)$ for the Spectralon[®] diffuse reflection standard of RASTA (b) together with the respective associated relative standard measurement uncertainties ($k=1$).

Calibration of the Spectral Radiance Factor $\beta_{l,0^\circ:45^\circ}(\lambda)$

The robot-based gonioreflectometer facility of PTB uses broadband irradiation of the sample with spectrally selected detection of the reflected radiation [6-8]. The unfiltered broadband irradiation is generated by a special sphere radiator [9]. This sphere radiator consists of a small integrating sphere with an internal diameter of 150 mm and a built-in 400 W quartz tungsten halogen lamp as a light source. It is located on a large rotation stage with a diameter of 1500 mm and can be rotated 360° around a 5-axis robot serving as a sample holder. The direction of the detection path is fixed due to its construction with a set of five mirrors and the use of a heavyweight 1/2-metre monochromator with 3 internal selectable gratings as the wavelength selective elements. The adjustment of the desired reflection geometry (0°:45° in this particular case) is accomplished by the combined adjustment of the rotation stage and the robot, which allows full angular control of the directed beams of incident and reflected radiation within the full half space above the surface of the sample (Spectralon[®] reflection standard in this case).

The covered wavelength range of the facility for calibrations of the radiance factor β is 250 nm to 1700 nm, with a 3 nm bandpass in the spectral range from 250 nm to 900 nm and a 6 nm bandpass within the 900 nm to 1700 nm range, depending on the gratings used. Four different detectors behind the monochromator are used for detecting the radiance signals of the incident and reflected beams: a solar blind channel photomultiplier (CPM) for measurements between 250 nm and 350 nm, a so-called yellow enhanced CPM between 300 nm and 450 nm, a silicon photodiode between 400 nm and 1100 nm and a cooled InGaAs photodiode (at -25 °C) between 1000 nm and 1700 nm. All the signals are detected with a picoammeter and transferred to a computer for data storage and analysis.

The relative standard measurement uncertainty ($k = 1$) for calibrations of the radiance factor β of highly reflecting samples ($\beta \approx 1$) ranges from 0.1 % in the visible and adjacent spectrum to 0.25 % in the IR at 1700 nm and to 0.6 % in the UV at 350 nm [6].

PROCEDURE II

Calibration of the Spectral Radiance $L_\lambda(\lambda)$

The calibration procedure II for RASTA was performed independently from procedure I, covering the entire spectral range of RASTA from 350 nm to 2500 nm. In this procedure, the spectral radiance $L_{\lambda,0^\circ:45^\circ}(\lambda)$ of RASTA was directly calibrated at the Spectral Radiance Comparator Facility (SRCF) [10, 11] of PTB by comparison to the spectral radiance of a high-temperature blackbody of known temperature.

The SRCF relies on the high-temperature blackbody HTBB3200pg as the national primary standard for the fundamental radiometric unit *spectral radiance*, the facility being applied for the realization and dissemination of the spectral radiance in the wavelength range from 220 nm up to 13 μm. The HTBB temperature is determined by two independent methods: traceable to the International Temperature Scale of 1990 (ITS-90) via a gold fixed-point blackbody and traceable to the PTB detector primary standard, the cryogenic radiometer, via absolutely calibrated filter radiometers.

Due to the RASTA design and the $0^\circ:45^\circ$ -viewing geometry, the SRCF had to be specially adapted to perform this calibration. This was achieved by implementation of a relay mirror in the optical path of the calibration setup and a high accuracy, 4-axis heavy load kinematic stage for the precise alignment of RASTA (Fig. 1, right). The reflectance of the relay mirror was calibrated separately under similar experimental conditions by means of two integrating sphere sources. The relative uncertainties for this calibration procedure range from 0.8 % in the visible up to 7.5 % at 2500 nm ($k = 1$).

In the overlapping spectral range of both calibration procedures (350 nm to 1700 nm), the calculated spectral radiance $L_{\lambda,0^\circ:45^\circ,\text{calc}}(\lambda)$ according to Eq. 1 from the calibration results of procedure I is in good agreement with the direct measurement of procedure II, i.e. well within the combined expanded uncertainty ($k = 2$) of both calibration procedures (figure 3).

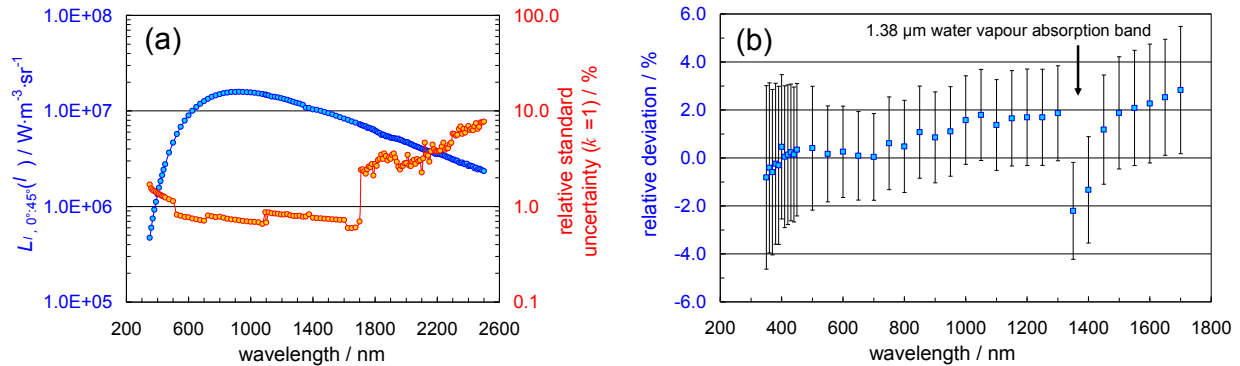


FIGURE 3. (a) Spectral radiance $L_{\lambda,0^\circ:45^\circ}(\lambda)$ of RASTA in $0^\circ:45^\circ$ viewing geometry and the associated relative standard measurement uncertainty ($k=1$). (b) Relative deviation of the measured spectral radiance $L_{\lambda,0^\circ:45^\circ}(\lambda)$ of RASTA according to procedure II from the calculated spectral radiance $L_{\lambda,0^\circ:45^\circ,\text{calc}}(\lambda)$ according to procedure I. The plotted error bars denote the combined expanded uncertainty of both calibration procedures ($k=2$).

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