Traceability of the Network for Detection of the Mesospheric Change (NDMC) to radiometric standards via a Near Infrared Filter Radiometer

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Abstract. We discuss a route to provide traceability to spectroradiometers that are operated within the network for detection of the mesospheric change. The spectrometers measure spectral radiance at low light levels (350 W m⁻² sr⁻¹ m⁻¹) at 1.55 μm. The traceability chain is based on a travelling reference source that is calibrated against a black body via a near infrared filter radiometer. In this paper the requirements, design and performance of the filter radiometer are discussed. It is demonstrated that the filter radiometer is suitable for transferring the scale at very low radiance levels, providing SI traceability to the traveling reference radiances within the required measurement uncertainty of 1%.

1. Introduction
The temperature of the mesopause, an atmospheric layer at an altitude of about 87 km, is one of the measures for the global temperature and has therefore been identified as an Essential Climate Variable (ECV) [1]. Ground-based mesopause measurements are performed within the Network for Detection of Mesospheric Change (NDMC), which comprises 55 stations. Within this world-wide network Ground-based Infrared P-branch Spectrometers (GRIPS) are used to investigate mesopause properties, such as composition and temperature. The GRIPS instruments observe air glow emissions from excited OH* and O* radicals and excited O₂. The mesopause temperature is derived from the relative intensities of rotational P-branch transitions in the Meinel band around 1.55 μm [2]-[4]. In order to determine this temperature with sufficiently low uncertainty, to allow for the measurement of temperature changes at the level of 1 K on a decade timescale, SI traceability to radiometric standards is required. Here, a very low radiance level of about 350 W m⁻² sr⁻¹ m⁻¹ needs to be measured, since this is the typical radiance level of OH* radicals in the relevant wavelength range of 1500 nm to 1600 nm.

We explore a traceability route based on a black body Travelling Radiance Source (TRSO), which is used as a reference for the GRIPS instruments. The TRSO is calibrated against a black body primary reference via a Near-InfraRed Transfer Radiometer (NIRTR). In this paper we focus on the development of the NIRTR designed for measuring low radiance levels for scale transfer within a 1% level of uncertainty.
2. Near infrared filter radiometer requirements and design

The method developed to provide SI traceability to GRIPS instruments is to expose the spectroradiometer to a known radiance level from a reference source (TRSO). The reference radiance source is a Planckian black body, in this case a transportable plate radiator, which is suitable for on-site measurements and sufficiently large to cover the field of view of the GRIPS detector (about 12°). The plate radiator is calibrated against a reference black body, using the filter radiometer (NIRTR) to transfer the scale. The traceability route is schematically depicted in Figure 1.

![Figure 1. Traceability chain from primary black body to GRIPS instrument](image)

2.1. Requirements

The requirements for the near-infrared transfer radiometer are based on the radiance level to be measured and on the measurement range and view angle (12°) of the GRIPS instrument. Furthermore, the NIRTR should be transportable and it should be possible to put it close to a black body radiator without affecting the NIRTR performance. To generate a typical radiance level of 350 W m⁻² sr⁻¹ m⁻¹, the reference black body and the TRSO will operate at a temperature of about 120 °C. The required measurement uncertainty on the radiances is estimated to be 1 %. The spectral range should cover the Meinel bands around 1.55 μm.

2.2. Optical design

The optical design of the NIRTR has been developed in Zemax and is shown in Figure 2. The light is collected with an objective lens with a diameter of 50 mm and a focal length of 80 mm. The field stop, having a diameter of 4 mm, is inserted to restrict the image size on the detector. The field stop is imaged 1 to 1 on the photodiode surface with 2 lenses of 30 mm focal length. The photodiode has a sensitive area with a diameter of 5 mm and is thus underfilled. The field of view of the system is limited by a Lyot stop (16 mm) that is inserted between the two collimating lenses. The Lyot stop is inserted such that size-of-source effects are minimized [5,6]. The filter is also inserted in the collimated beam between the lenses. The filter transmission is centered around 1.55 μm, with a bandwidth of 65 nm. As a detector a thermo-electrically cooled InGaAs detector (Hamamatsu G112180) has been selected. All components are mounted along a common optical axis in a cage system consisting of four graphite epoxy rods, which minimize effects of thermal expansion. The whole instrument is shielded with a light-tight insulated housing. The front panel and bottom plate are temperature stabilized by an embedded water cooling system. A shutter is mounted in front of the objective lens to perform dark measurements.
2.3. Signal and noise levels

Based on the design, the signal level has been estimated for a black body at a temperature of 120 °C. The signal $S(T)$ of the NIRTR as a function of temperature $T$ is:

$$S(T) = \int_{\lambda_1}^{\lambda_2} G \cdot R(\lambda) \cdot \tau(\lambda) \cdot \Omega \cdot A \cdot L(\lambda, T) d\lambda,$$

(2.1)

where $G$ is the gain of the amplifier, $R(\lambda)$ is the spectral responsivity of the detector, $\tau(\lambda)$ is the transmittance of the interference filter, $L(T, \lambda)$ is the radiance of a black body at a temperature $T$, $\Omega$ is the solid viewing angle of the detector and $A$ is the illuminated area of the detector. The lens transmission and geometrical parameters (solid viewing angle of the detector, illuminated detector area) have not been measured, but are based on the design. The detector absolute spectral responsivity and the filter transmission (including angular dependence) have been calibrated by PTB and are used here to estimate the expected signal level. For the calibration of a radiance source like the TRSO with the NIRTR, only the relative spectral dependence of responsivity and transmittance needs to be considered. Note that equation 2.1 is only used to estimate the signal level. The calibration of the NIRTR as a whole will take place against a reference black body.

Based on the design parameters as summarized in Table 1, the current generated by the photodiode is estimated to be $1.3 \times 10^{-10}$ A for a radiance level of 350 W m$^{-2}$ sr$^{-1}$ m$^{-1}$. With a gain of $10^8$ selected at the trans-impedance amplifier, this leads to a signal of $1.3 \times 10^{-2}$ V.
Table 1. Overview of input quantities for signal level estimation

| Quantity                                      | Value                                                                 |
|-----------------------------------------------|----------------------------------------------------------------------|
| Illuminated detector area A                   | $\pi \times (2 \text{ mm})^2$                                        |
| Solid viewing angle at detector               | 0.31 sr                                                              |
| Filter transmission                           | Centered around 1550 nm, width 65 nm, based on measurement data of PTB |
| Transmission of the system (taking into account losses due to reflection from the interfaces) | 0.985                                                                |
| Black body emissivity                         | 0.95                                                                |
| Black body temperature                        | 120 °C                                                              |
| Photodiode responsivity                      | 1.1 A/W at 1550 nm                                                  |
| Gain setting DLPCA-200 G                      | $10^8$                                                              |

To estimate the expected noise level, the following noise contributions have been considered: the Noise Equivalent Power (NEP) generated by the photodiode, the equivalent input noise current of the current amplifier and the noise contribution of the nanoVolt meter. The NEP power of the G12180 photodiode is specified as $1.5 \times 10^{-14}$ W/√Hz. The bandwidth has been limited to 10 Hz, as set on the transimpedance amplifier. In Table 2 the input parameters for the noise estimation are summarized. A total noise equivalent output voltage of 6.1 μV is expected. At an estimated signal level of $1.3 \times 10^{-2}$ V, this corresponds to a signal-to-noise ratio of 0.05 %.

Table 2. Overview of input quantities for noise level estimation

| Quantity                                      | Value                                                                 |
|-----------------------------------------------|----------------------------------------------------------------------|
| NEP G12180, in 10 Hz bandwidth,               | $4.7 \times 10^{-14}$ W                                              |
| Corresponding voltage noise                   | $4.3 \times 10^{-6}$ V                                               |
| Equivalent input noise current DLPCA-200      | $4.1 \times 10^{-6}$ V                                               |
| Noise contribution HP34420A @ 100×10^{-6} V/V | $1.3 \times 10^{-6}$ V                                               |
| Total noise equivalent output voltage of system | $6.1 \times 10^{-6}$ V                                               |

3. Performance and measurement results

The signal level and size-of-source effects (SSE) have been measured by exposing the NIRTR instrument to the radiance from a primary black body (water heat pipe with 60 mm aperture diameter) with a set temperature of 120 °C. SSE have been determined by measuring the signal level as a function of distance to the black body aperture. Over a distance ranging from the closest position possible (0 mm) to 140 mm, corresponding to opening angles from 61° to 18°, the signal change is within the requirements, having a standard deviation of 0.2 % (see Figure 3). For larger distances (opening angle below 18°) the NIRTR signal drops because it starts looking outside the black body aperture. This measurement illustrates the well-defined field of view of the NIRTR. Currently SSE is not expected to be the dominant contribution in the calibration of a GRIPS instrument. However, further reduction of SSE could be obtained by matching the opening angles at which the calibration takes place of NIRTR and, subsequently, the TRSO and the GRIPS instrument.

The NIRTR has been calibrated against the water heat pipe black body at PTB. From the measurement results shown in Figure 4 (left), which are obtained over 3 days of measurements, good reproducibility is observed. The noise equivalent temperature difference (NETD) based on stability measurements over 3 days is 23 mK at 120 °C (1 s averaging time). This corresponds to an uncertainty contribution of 0.14 % for the measured radiance. Based on the reproducibility of this calibration and
the uncertainty resulting from SSE, the uncertainty on the calibration of the NIRTR is estimated to be 0.5 \% (expanded uncertainty, coverage factor $k=2$).

![Figure 3](image)

**Figure 3.** Size-of-source measurement: relative signal level as a function of opening angle. The standard deviation based on the range 18° to 61°, equals 0.2 \%.

Subsequently, the radiance from the TRSO has been measured by the NIRTR. The difference between the set temperature and the measured radiation temperature, as based on the radiance measurement, has been plotted against the set temperature in Figure 4 (right). The difference between radiation temperature as measured in the 1.5 $\mu$m to 1.6 $\mu$m range and the set temperature results from a higher emissivity in the 1.5 $\mu$m to 1.6 $\mu$m compared to the emissivity in the 8 $\mu$m to 14 $\mu$m range (the TRSO has a factory calibration for radiation temperatures in the 8 $\mu$m to 14 $\mu$m range). In four characterization campaigns over one year the NIRTR was successfully applied to verify the long-term stability of the TRSO (Figure 4 right) and as a next step the calibrated TRSO is available to providing traceability to the GRIPS instruments.

![Figure 4](image)

**Figure 4.** Left: stability of the filter radiometer expressed in mK, as measured over 3 consecutive days and for various temperatures of the water heat pipe. The noise equivalent temperature difference derived from these data is 23 mK. Right: calibration of the TRSO (Fluke 4180), temperature difference between set temperature and measured radiation temperature with the NIRTR. The relatively large difference results from the fact that the TRSO has a factory calibration for application in the 8 $\mu$m to 14 $\mu$m range.
4. Conclusions
We have presented a traceability chain for calibration of Ground-based Infrared P-branch Spectrometers, based on a travelling radiance source, that obtains its scale from a reference black body via a transfer filter radiometer. In particular, the design and performance of the NIRTR has been discussed and investigated, showing that the stability and size-of-source effects are sufficiently low to achieve a measurement uncertainty below 1% for the radiance calibration of a black body radiator.

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