

# Monochromator Based Calibration of Radiance Mode Filter Radiometers for Thermodynamic Temperature Measurement

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**Abstract.** Filter radiometers have been calibrated for measurement of the thermodynamic temperature in radiance mode. A new spectral radiometric calibration scheme has been adopted which requires only a monochromator system and can be implemented without tuneable lasers. A lens transmittance measurement method is discussed which enables simultaneously the correction of size-of source effect to infinite source diameter.

## Introduction

Determination of thermodynamic temperature of the transition temperature of metal (carbide)-carbon eutectics is a prerequisite for their application as temperature reference points. Such measurements based on absolute spectroradiometric technique is commonly made in two ways: either using filter radiometers with [1,3] or without imaging optics [2]. The latter (irradiance mode) has the advantage that it does not involve characterization of the lens transmittance and the size-of-source effect (SSE), which can sometimes complicate the procedure. However, it has the disadvantage that the blackbody source needs to be large enough compared to the geometry of the filter radiometer apertures. For metal (carbide)-carbon eutectics, current research effort on the fixed points is focussed on establishing small aperture cells, typically 3 mm in diameter, mainly due to the restriction in available high-temperature furnace dimension. Therefore, the preferable choice for the filter radiometer configuration is the former (radiance mode).

The authors have carried out a joint project to measure in radiance mode the melting temperatures of Re-C and Pt-C eutectic fixed points, with also a measurement of the Cu point performed as verification [4]. In the present paper, the calibration scheme is described. It is novel from the point of view that it is based only on existing facilities at the BIPM in contrast to the previously reported schemes in radiance mode which depend on tuneable laser based spectral characterization in combination with an integrating sphere [1,3].

## Measurement Principle and Setup

The measurement setup of the thermodynamic temperature consists of a filter radiometer assembly (consisting of a photodiode, an interference filter, and a precision aperture), and a lens equipped with a lens aperture. The components are mounted on a granite linear bench of 2 m length. The lens focuses the image of the fixed point source aperture onto the filter radiometer aperture, overfilling the latter. The distance between the two apertures, which is around 1800 mm, is measured by means of a laser interferometer.

The diamond-turned apertures, made of brass and with land of 100  $\mu\text{m}$ , have diameters of 5 mm for the filter radiometer apertures, and 18 mm for the lens aperture. The latter dimension was restricted by the capability of the aperture measurement system.

Two of filter radiometers were made, one with an interference filter with nominal central wavelength of 700 nm and another with 800 nm, both having a bandwidth of 20 nm. The filter radiometer housings were temperature controlled by circulating water. Initially, the detector was placed directly behind the filter. However, fluorescence from the filter was observed in the spectral responsivity measurement, described below, which showed up as an out-of-band response of the order of  $10^{-4}$ . Increasing the detector-filter spacing to 35 mm reduced this effect to an insignificant level. No tilt was introduced in the alignment of the filter and the detector.

Following Planck's law, the voltage  $V$  measured at the output of the current-to-voltage amplifier is a function of the radiance of the source, and hence of the thermodynamic temperature  $T$  [4].

$$V = R_{\text{ampli}} \cdot \frac{A_{\text{FR}} \cdot A_{\text{L}}}{d^2} \cdot R_{\text{opt}} \cdot \frac{2hc^2}{n^2} \cdot \varepsilon_{\text{BB}} \cdot \int \frac{S_{\text{FR}}(\lambda)}{\lambda^5 (e^{hc/n\lambda kT} - 1)} d\lambda \quad (1)$$

where  $R_{\text{ampli}}$  is the gain of the amplifier,  $A_{\text{FR}}$  the filter radiometer aperture area,  $A_{\text{L}}$  the lens aperture area,  $d$  the distance between the two apertures,  $R_{\text{opt}}$  the term including lens transmittance, size-of-source effect, diffraction and other effects as described hereafter,  $h$  the Planck's constant,  $c$  the speed of light,  $k$  the Boltzmann constant,  $n$  the refractive index of standard air,  $\varepsilon_{\text{BB}}$  the emissivity of the blackbody,  $S_{\text{FR}}(\lambda)$  the spectral responsivity of the filter radiometer,  $\lambda$  the wavelength in air in the range covered by the filter radiometer.

## Calibration

The calibration of the filter radiometer consists of 1) absolute spectral radiometric calibration 2) aperture area measurement and 3) lens transmittance and SSE measurement. The spectral radiometric calibration involves only the filter radiometer assembly, with the monochromator output beam collimated to be parallel and homogeneous at the filter radiometer aperture plane, simulating the situation during measurement of the blackbody radiation. The lens transmittance and SSE measurement is made with another facility in almost the same configuration as the measurement of the

blackbody, with the aim of investigating any multiple reflections, diffraction or stray light effect.

### 1) Absolute spectral responsivity measurement

The spectral responsivity measurement method follows what has already been described in [5], with minor but important modifications to adapt to conditions specific to the current system. The monochromator is a Czerny-Turner type double-grating system in additive configuration (manufacturer: Jobin Yvon), with focal distance of 60 cm, equipped with a grating of 1200 lines/mm. The halogen lamp source is focussed onto the entrance slit by a lens. The output monochromatic beam is collimated by a spherical mirror of focal distance 280 mm. The reference trap detector (also with a 5 mm aperture) and the filter radiometer are mounted on a computer controlled rotational stage so that they can alternately be placed in exactly the same position in the output optical path with the beam overfilling the aperture. The trap detector absolute spectral responsivity  $S_{\text{trap}}(\lambda)$  is calibrated at discrete laser wavelengths with a cryogenic radiometer and then interpolated.

One major source of uncertainty is related to the positioning of the apertures, combined with the inhomogeneity in the irradiance. The trap detector / filter radiometer aperture is placed at focal distance from the mirror, which is the image plane of the grating and therefore the position where the irradiance uniformity is expected to be the best. However, there was still a considerable gradient in the irradiance of 1 to 4 %/mm. To reduce this inhomogeneity, a linear gradient filter was inserted before the entrance slit. By adjusting the orientation and the distance to the slit, it was possible to reduce the nonuniformity by about a factor of 10.

The spectral responsivity of the filter radiometer  $S_{\text{FR}}(\lambda)$  is given by the following [6]:

$$S_{\text{FR}}(\lambda) = \frac{A_{\text{trap}}}{A_{\text{FR}}} \cdot \frac{i_{\text{FR}}(\lambda)}{i_{\text{trap}}(\lambda)} \cdot S_{\text{trap}}(\lambda) \quad (2)$$

where  $i_{\text{trap}}(\lambda)$  and  $i_{\text{FR}}(\lambda)$  are the detected current of the filter radiometer and the trap detector, respectively.  $A_{\text{trap}}$  is the trap detector aperture area.

### 2) Aperture area measurement

Applying eq. (2) into eq. (1), one finds that  $A_{\text{FR}}$  is cancelled. Therefore, of the four apertures involved, precise knowledge only of  $A_{\text{trap}}$  and  $A_{\text{lens}}$  are necessary. These were measured using the laser beam superposition technique [6].

### 3) Lens transmittance and SSE measurement

SSE is caused by imperfection in the imaging optics, such as refraction and scattering at the lens, aperture diffraction, and multiple reflections. Multiple reflections between lens and apertures would cause an unwanted increase in the signal, and should be eliminated from the system by careful alignment and optical arrangement. All others would not have any effect to the signal if the source extended to infinite diameter. How-

ever, with finite sources, this will cause reduction in the signal and should be compensated.

Measurement of the SSE function conducted with a large aperture integrating sphere source equipped with halogen lamps indicated that it was still not saturating at the maximum measurable source diameter of 70 mm, due to the relatively large diffraction caused by the limited size of the lens aperture. Therefore it was not possible to compensate for SSE towards infinite source diameter.

To overcome this problem, a new scheme was devised [4] which combines the SSE and the lens transmittance corrections. The SSE correction is made up to 40 mm source diameter. At this diameter, correction is made from radiance mode to irradiance mode, which includes the lens transmittance compensation. The correction factor is just the ratio of the signal obtained with and without the lens with a 40 mm diameter source. Once corrected to irradiance mode, the correction to infinite source diameter can be conducted by simply taking into account diffraction effect, theoretically given in [7], since all other lens related imperfections are no longer there.

## Measurement of the fixed-point temperatures

The calibration scheme has been successfully applied to fixed-point temperature measurements [4]. The freezing temperature of the primary reference copper point of the BNM-INM (currently LNE) was measured linking it to the filter radiometer through a transfer copper-point furnace. The measured thermodynamic temperature given as the average of the two filter radiometers was 0.148 K higher than the ITS-90 value, with a measurement uncertainty of 0.154 K ( $k=2$ ). Although limitation in time for completion of the project restricted the measurement accuracy to be less than the highest achievable, the above result confirms the validity of the current calibration scheme and give confidence in the transition temperatures of Re-C and Pt-C eutectic fixed points measured at the BIPM with uncertainty of the order of 0.6 K and 0.3 K respectively.

The demonstrated applicability of the scheme to measurement of eutectic fixed points opens a way for laboratories without tuneable lasers to take part in the determination of their thermodynamic temperatures.

## References

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