Comparison of the absolute detector-based spectral radiance assignment with the current NIST-assigned spectral radiance of tungsten strip lamps

H. W. Yoon and C. E. Gibson

Abstract. Using a high-temperature black body (HTBB) and filter radiometers calibrated for absolute spectral power responsivity, the spectral output of the black body, whose radiance temperature was determined using the filter radiometers, was used to assign spectral radiance to tungsten strip lamps with a prism-grating monochromator. The spectral radiance of the HTBB was also determined using signal ratios to a tungsten strip lamp calibrated using a scale derived from the radiometric temperature determination of a gold-freezing-point black body. The radiance temperatures found using the two methods were in agreement to 0.5 K near 2900 K, and from 260 nm to 1050 nm, the spectral radiance of the HTBB did not differ more than 0.5 % in radiance from a single-temperature Planck's law as determined using the tungsten strip lamp.

1. Introduction

The current NIST spectral radiance and spectral irradiance scales are both based on the absolute radiance temperature determination of the gold-freezing-point black body [1, 2]. The radiance temperature at 654.6 nm is assigned using the gold-fixed-point black body to a vacuum tungsten strip lamp maintained at a radiance temperature of 1337.33 K and then transferred again to another lamp at 1530 K. The radiance temperature of a variable-temperature black body (VTBB) is assigned using the two vacuum lamps. The spectral radiance of a tungsten strip lamp is in turn assigned using the VTBB. The spectral irradiance scale is established using the spectral radiance scale. The spectral radiance of an integrating-sphere source (ISS) with a high-precision aperture is assigned using the VTBB, and knowing the spectral radiance of the ISS, the spectral irradiance at a set distance from the aperture of the ISS is established. The ISS is used to assign the spectral irradiance of a number of FEL lamps, which are in turn used to maintain the spectral irradiance scale on a working basis.

The path to establishing a spectral irradiance scale is long and requires many artefacts, primarily because the spectral output of the 1000 W FEL lamp has a spectral shape closer to a 3000 K black body than the gold-freezing-point black body at 1337.33 K [3]. At many standards laboratories, the recognition of such difficulties has led to active research efforts into alternative methods of establishing a spectral irradiance scale [4]. The development of high-temperature pyrolytic graphite black bodies and highly accurate spectral responsivity scales based on the cryogenic radiometer has allowed direct spectral comparisons of the FEL lamps and black bodies using filter radiometers for determinations of the thermodynamic temperatures [5]. Although some national laboratories have already established their spectral radiance and irradiance scales based on these new techniques, the comparisons between their old scales and the new scales have not been well documented.

Our work addresses the following basic questions which need to be answered in the process of establishing a detector-based spectral radiance scale: What is the agreement in radiance temperature between the detector-based filter radiometers and those found using ratios to the gold-freezing-point black body? Can the spectral radiance of the HTBB be described by a single-temperature Planck's law? What is the agreement between the current spectral radiance scales based on the gold fixed point and the new detector-based scales?

2. Experimental procedure and results

The fundamental step in establishing a detector-based spectral radiance scale is the accurate determination of thermodynamic temperatures. The thermodynamic temperatures are determined using filter radiometers calibrated for absolute spectral power responsivity in the NIST Spectral Comparator Facility (SCF) with a scale derived from the NIST High Accuracy

H. W. Yoon and C. E. Gibson: Optical Technology Division, National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899, USA.

Cryogenic Radiometer [6]. These filter radiometers consist of temperature-stabilized broadband filters and silicon photodiodes, with high-precision apertures for determination of spectral irradiance responsivity from the spectral power responsivity [7, 8]. The spectral responsivities of the filter radiometers are chosen for coverage in the most accurate spectral region of the SCF. The filter radiometers are calibrated using the output from a monochromator, which underfills the high-precision aperture of the filter radiometers. Figure 1 shows the spectral power responsivities of the three filter radiometers. These filter radiometers were previously used to measure the radiometric temperatures of a variable-temperature black body whose radiance temperatures were also determined using radiance ratios from the gold-freezing-point black body. The agreement between the radiance and radiometric temperatures was better than 0.5 K in the temperature range 2200 K to 2800 K [9]. The long-term temporal stability of the filter radiometers is extremely good, exhibiting a change in spectral responsivity of less than 3 parts in 10^3 in two years [10].
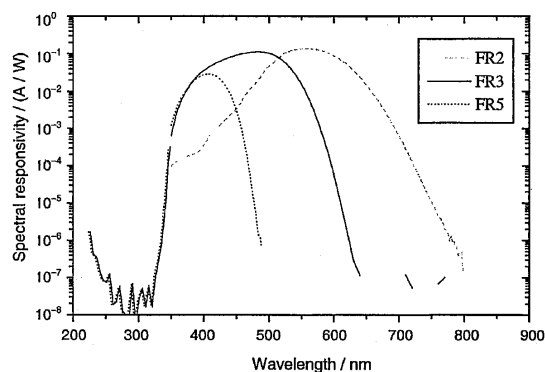

Figure 1. Spectral power responsivities of the three filter radiometers as measured on the NIST SCF.

To achieve the high temperatures necessary to calibrate a 1000 W FEL lamp, the coaxial pyrolytic graphite HTBB was operated at near 2900 K for all the experiments described in this work. The HTBB was temperature stabilized with an optical feedback control using a temperature-stabilized photometer viewing the rear side of the cavity bottom. All measurements of the spectral radiance using the monochromator were bracketed by measurements with the filter radiometers to compensate for temporal drift of the radiance temperature. A water-cooled high-precision circular aperture with a diameter of 9.9933 mm was placed in front of the HTBB for defining the source area at a distance of approximately 25 mm from the opening of the HTBB.

In comparisons of radiance temperatures using different instruments, the viewing region of each instrument at the HTBB cavity bottom, with an inner diameter of 32 mm, should be as nearly the same as possible in order to avoid differences arising from spatial inhomogeneities of the black body. The spatial uniformity of the HTBB, shown in Figure 2, was measured using the monochromator in an $f/30$ geometry, corresponding to viewing an area of 1 cm in diameter on the back wall. The spatial uniformity is similar to other scans on this type of HTBB [11]. The one-dimensional scans were made at 650 nm with the focus of an off-axis spherical mirror at the opening of the HTBB. The water-cooled aperture was removed for the one-dimensional scans. Seen in Figure 2, the spectral radiance differs by less than 3 parts in 10^3 from edge to edge of the 10 mm diameter water-cooled aperture if this aperture is used. The water-cooled aperture was used in measurements of both spectral radiance and spectral irradiance. In spectral radiance measurements with the monochromator, an $f/16$ geometry, corresponding to viewing a region of the cavity bottom about 1.9 cm in diameter, was used. The distance between the filter radiometers and the black-body aperture was set to near 32 cm to achieve an $f/23$ geometry, corresponding to viewing a 2.3 cm diameter region of the cavity bottom.
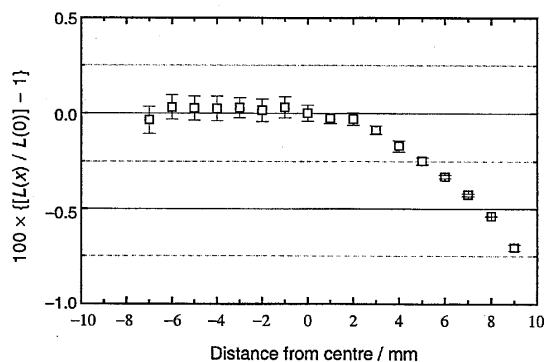

Figure 2. One-dimensional scan of the HTBB using the monochromator in an $f/30$ geometry. $L(0)$ denotes the spectral radiance at 650 nm at the centre of the HTBB opening and $L(x)$ the spectral radiance at a distance, x, from the centre. The uniformity is better than 3 parts in 10^3 over the central region corresponding to the 10 mm diameter water-cooled aperture used with the filter radiometers. The error bars represent the Type A standard uncertainties of the measurements.

The radiance temperature of the HTBB was determined using the following measurement equation. For filter radiometers the response, S, is given by

$$S = \frac{G\pi r_{BB}^2 \pi r^2 (1 + \delta)}{D^2} \varepsilon \int \rho(\lambda) L_\lambda(T) \, d\lambda, \quad (1)$$

where ε is the emissivity and ρ is the absolute spectral power responsivity. The geometric factors D and δ are given by $D^2 = d^2 + r^2 + r_{BB}^2$ and $\delta = r^2 r_{BB}^2 / D^4$, where r_{BB} and r are the radius of the black-body aperture and the filter radiometer (FR) apertures, respectively; d is

the distance between the FR aperture and the black-body aperture; G is the preamplifier gain; and L_λ is the Planck radiation law.

Figure 3 shows the measurements of the black-body temperatures as a function of time using the three filter radiometers. Each time sequence corresponds to an interval of about 50 s during which the FRs in sequence measure the radiance temperature of the HTBB. The change in radiance temperature near the middle of the plot in Figure 3 indicates where the black-body spectral radiance was measured using the double monochromator over an interval of about 20 min. The optical feedback signals during the measurements did not indicate any abrupt jumps in the radiance output, and thus a linear interpolation of the temperature is used.
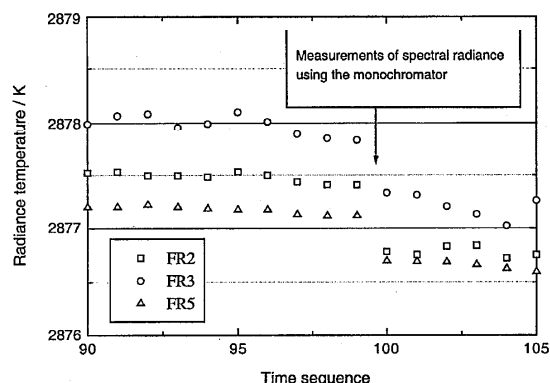

Figure 4. HTBB radiance temperatures versus wavelength (open squares) determined using the spectral radiance of the tungsten strip lamp. The solid circle, square, and triangle indicate the radiance temperatures found using the filter radiometers FR5, FR3, and FR2, respectively.

Figure 3. Radiance temperatures measured using the filter radiometers against time intervals (of about 50 s each). The abrupt change in the radiance temperature near the middle of the plot is where the measurements (taking about 20 min) of spectral radiance were performed.

The spectral radiance of the black body was verified by comparisons with an argon-filled tungsten strip lamp (TSL), Q122, which was calibrated in the NIST Facility for Automated Spectroradiometric Calibrations (FASCAL) [2]. The measurements of spectral radiance were performed using a prism-grating double monochromator with a Si photodiode detector [12]. The spectral radiance of the HTBB was determined using

$$L_{\lambda,\text{HTBB}} = L_{\lambda,\text{TSL}}\, S_{\text{HTBB}}/S_{\text{TSL}}, \qquad (2)$$

where $L_{\lambda,\text{TSL}}$ is the spectral radiance of the lamp and S_{TSL} the spectral response when viewing the lamp with the monochromator. The spectral radiance of the HTBB was converted to radiance temperature using Planck's law. Figure 4 shows the radiance temperatures determined using ratios from the tungsten strip lamp shown along with the thermodynamic temperature determinations using the filter radiometers. The average of the radiance temperature measurements using the three filter radiometers is 2877.20 K, and the average of
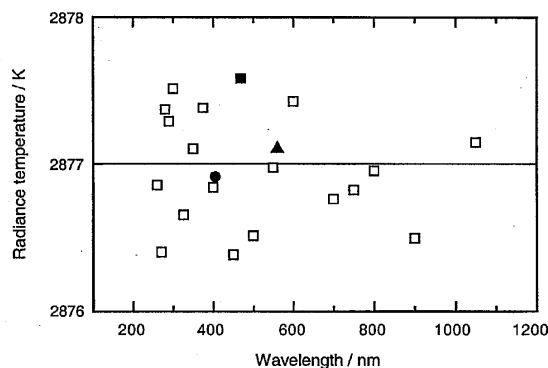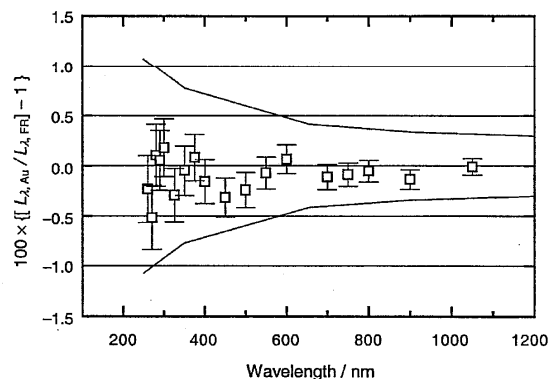

Figure 5. The relative difference in spectral radiance of the HTBB determined using the tungsten strip lamp from the Planck radiance at $T = 2877.2$ K determined using the filter radiometers. $L_{\lambda,\text{Au}}$ and $L_{\lambda,\text{FR}}$ denote the spectral radiance of the HTBB found using the tungsten strip lamp and the filter radiometers, respectively. The error bars indicate the ± 0.5 K radiance temperature uncertainty converted to spectral radiance uncertainty using the Wien approximation.

the temperature determinations using the tungsten strip lamp is 2876.94 K. The small amount of scatter in the data is within the uncertainties of the measurements, and the results are in agreement to 0.3 K with the average of the thermodynamic temperatures found using the filter radiometers.

Figure 5 shows the relative difference in the spectral radiance from the Planck radiance at (2877.2 ± 0.5) K, and the solid lines indicate the expanded uncertainties in the spectral radiance of the tungsten strip lamp. The error bars indicate the uncertainty of ± 0.5 K converted to uncertainties in spectral radiance using the derivative of the Wien approximation with temperature [9]. The temperature used in Figure 5 was determined from a mean of the radiance temperatures found using the three filter radiometers in Figure 3, interpolating between the

radiance temperatures before and after the spectral radiance measurements. In Figure 5 there is no evidence of spectral mismatch between the HTBB and the tungsten strip lamp, which would be evidenced by a noticeable curvature of the spectral differences in the ultraviolet wavelength region. The very good agreement shown in Figures 4 and 5 confirms that the NIST spectral radiance scale is ultimately consistent with the thermodynamic temperature scale within the combined uncertainties of the measurements.

3. Discussion

We have shown that the current source-based spectral radiance scale at the NIST is consistent with the detector-based spectral radiance scale. In the near future, the process of scale realization for spectral radiance will be changed from the present source-based scale to the detector-based scale. The scale realization will begin with the radiance temperature determination of the HTBB followed by the radiance temperature determination of the VTBB from radiance ratios using the monochromator. The agreement of the HTBB with a single-temperature Planck law will then be tested, relying on the high emissivity of the VTBB, using radiance ratios of the HTBB to the VTBB at wavelengths from 250 nm to 2500 nm. Once the HTBB has been verified as sufficiently Planckian, then the two vacuum tungsten strip lamps will be calibrated for radiance temperature at several wavelengths. As the HTBB is difficult to use on a daily basis, the spectral radiance scale will be maintained as a radiance temperature scale relying on the temporal stability of the two vacuum tungsten strip lamps.

Although the uncertainty of the thermodynamic temperature determination using the HTBB is at present equivalent to those using radiance ratios to the gold-fixed-point black body, improvements in the absolute spectral irradiance responsivity calibrations of filter radiometers will lead to lower uncertainties in the radiance temperature determinations of the HTBB. As the typical transfer standards of spectral radiance have lower radiance temperatures than the HTBB, the reduction in uncertainty of the HTBB leads to lower uncertainties at the lower temperatures:

$$u\left(T_{\mathrm{VTBB}}\right) = u\left(T_{\mathrm{HTBB}}\right) T_{\mathrm{VTBB}}^2 / T_{\mathrm{HTBB}}^2, \qquad (3)$$

where T_{VTBB} denotes the temperature of the variable-temperature black body and T_{HTBB} that of the high-temperature black body, with the respective uncertainties in temperature.

4. Conclusions

We have shown that the spectral radiance scale at the NIST derived from the absolute radiance temperature determination of the gold-freezing-point black body is in agreement with that derived from a thermodynamic temperature determination using detector-based filter radiometers. The source-based spectral radiance assignment of a high-temperature black body was found to agree to better than 5 parts in 10^3 from 250 nm to 1050 nm with the detector-based assignment. We describe a procedure for the detector-based scale realization of the spectral radiance that will lead to lower uncertainties in the NIST spectral radiance scale.

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