THE DETERMINATION OF EMISSIVITY OF THE VARIABLE-TEMPERATURE BLACKBODY USED IN THE DISSEMINATION OF THE US NATIONAL SCALE OF RADIANCE TEMPERATURE

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ABSTRACT

The emissivity of the variable-temperature blackbody (VTBB) used to disseminate the US radiance temperature scale was determined using a pyrometer with narrow-band spectral filters centered at 650 nm, 900 nm, and 1000 nm. Such measurements are needed to compare the accuracies of the radiance temperature determinations of pyrometers which could have peak sensitivities at any arbitrary wavelength. At the three wavelengths, separate, independent determinations of the radiance temperature of the VTBB were performed from 1200 K to 2800 K via spectral radiance ratios to the Au fixed-point blackbody as described in the International Temperature Scale 1990 (ITS-90). In order to determine the radiance temperatures using the spectral radiance ratios, the relative spectral responsivity of the pyrometer was measured in the NIST Spectral Comparator Facility. The field stop of the optical system restricted the target area to 0.6 mm by 0.8 mm focused at the bottom of the 25.4 mm diameter cavity, and the temperature variations of the cavity bottom were found to be < 0.2 K over a diameter of 8 mm. Due to the temperature uniformity and the small viewing area of the pyrometer, the radiance temperature measurements were analyzed using a constant, or gray-body emissivity model. The measured emissivity of the VTBB was found to be 0.9985 ± 0.0005 (k = 1).

1. INTRODUCTION

The two defining characteristics of any blackbody are its thermodynamic temperature and its spectral emissivity. In the Radiance Temperature Calibration Laboratory (RTCL)[1] of the National Institute of Standards and Technology (NIST), the radiance temperature of a variable-temperature blackbody (VTBB) is determined using radiance ratios to the gold freezing-point blackbody (GPBB)[2] using the Photoelectric Pyrometer (PEP) with a narrow spectral filter (655.3 nm). In-turn, other pyrometers are calibrated using the VTBB. Since the radiance temperature of the VTBB is assigned only at a single wavelength with the PEP, the spectral emissivity of the VTBB has to be well characterized in order to calibrate pyrometers with spectral responsivity at wavelengths different from the PEP.

Since any opening that allows optical access changes the radiative properties of the blackbody from the ideal situation described by the Planck radiance law, innumerable approaches exist to describe the spectral emissivity of an arbitrary blackbody cavity. If the cavity has an isothermal temperature distribution then analytical methods can be used to determine the emissivity[3], and if the cavity is non-isothermal, then numerical methods, such as Monte Carlo methods[4], can be used to also estimate the emissivity. The emissivity can also be estimated from measurements of the blackbody reflectance and the geometry[5]. Although these studies can be used to optimize the initial physical design of the cavity, experimental values of the spectral dependence of the radiance temperatures are still necessary to verify the calculated spectral emissivity of the blackbody. A direct approach to determination of the emissivity of a blackbody is to compare the radiance temperatures of the blackbody-under-test at various wavelengths to those from a known, high-emissivity blackbody.

We describe the determination of the emissivity of the VTBB by comparison to the GPBB by the measurements of radiance temperatures with narrow-band pyrometer that utilizes a filter wheel. The filters with about 10 nm bandpass are centered at wavelengths of 650 nm, 900 nm, and 1000 nm. This new instrument is called the modified PEP. The measurements were performed from 1200 K to 2800 K in intervals of 100 K at each of the three wavelengths resulting in separate, independent realizations of ITS-90 at the three respective wavelengths. The radiance temperatures at the three wavelengths were analyzed using a constant, gray-body emissivity model due to the spatial uniformity of the radiance temperatures and the small target area at the bottom of the cavity.

2. EXPERIMENTAL CONFIGURATION

The US National Scale of Radiance Temperature is maintained and disseminated from the RTCL at the NIST. For scale realizations, the radiance temperatures of the VTBB are found using radiance ratios to the GPBB and are assigned using a well-characterized single wavelength PEP at 655.3 nm with a bandwidth of 1.1 nm. Both the GPBB and the PEP were developed using NIST designs and manufacture. The GPBB consists of a central cavity with a 3 mm diameter opening surrounded by about 1.3 kg of high-purity (99.9999 %) gold. The cavity with the gold is in-turn surrounded by a sodium heat-pipe for increased thermal uniformity and thermal resistance, resulting in time duration of the freeze to be about 40 minutes. The resulting calculated emissivity of the GPBB is estimated to be 0.9999 (+0.0001)[6]. For routine calibrations, since the GPBB is difficult to operate on a daily basis, the radiance temperature scale is transferred to a stable, vacuum tungsten-strip lamp (GPL) with the current stabilized to match the spectral radiance of the GPBB at 655.3 nm. The radiance temperature assignments of the VTBB are performed using the GPL as proxy for the GPBB.

The VTBB is a commercially designed blackbody consisting of a 25.4 mm diameter cavity with a middle partition acting as the cavity bottom. The cavity bottom lies at a depth of 14.45 cm from the end caps, and modifications have been made to the VTBB to improve the temperature uniformity such as the installation of the end-cap extensions. The temperature uniformity of the VTBB cavity bottom has been mapped using a narrow field-of-view radiometer and found to be uniform to < 0.2 K over the 8 mm central area of the cavity bottom. The temperature control of the VTBB is performed using an optical feedback control to the power supply using a detector, which views the rear of the cavity. The feedback control system regulates the VTBB temperature to ± 0.1 K during typical operations.

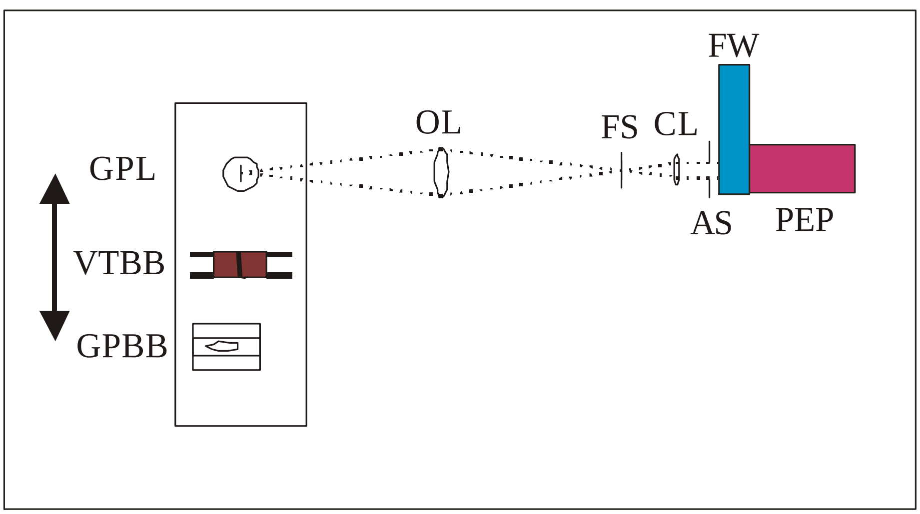

Figure 1: The schematic of the RTCL with the VTBB, GPBB and the GPL lamp along with the modified PEP.

All the radiance temperature measurements were performed using the modified PEP. The modifications consisted of the addition of a filter wheel (FW) with the three narrow-band interference filters and the use of the temperature-stabilized silicon photodiode as the detector. The optical elements from the objective lens (OL) to the aperture stop (AS) were not modified. The OL, with a diameter of 5.8 cm, is placed at 64 cm from the VTBB cavity bottom and from the field stop resulting in a 1:1 ratio between the object distance and the image distance. The field stop consists of a metallic mask with an opening of 0.6 mm wide by 0.8 mm high. The collimating lens (CL) has a 12.94 cm focal length. The filter wheel, with the 50.8 cm diameter interference filters, was aligned to the collimated beam. The silicon detector has an active area of 5.8 mm by 5.8 mm resulting in the optical beam overfilling the detector in a nominal f/22 geometry. Since the modified PEP viewed all the sources with the same optical system, the failure to collect all the collimated light was not deemed detrimental to the performance of the system.

The measurements were performed over a 1 week interval in January 1999. Before the measurements of the radiance temperatures of the VTBB, the radiance temperature scale of the GPL was assigned at 650 nm, 900 nm, and at 1000 nm using the GPBB and the modified PEP. Since the VTBB stabilizes at a constant temperature after a decrease in temperature with a slower time delay than after an increase, the initial VTBB temperatures were set near 2800 K and then decreased in steps of 100 K. At each temperature, the modified PEP was used to measure the tungsten-strip lamp SL20 and then used to assign the VTBB radiance temperature.

3. RESULTS

The temperature of the VTBB was found using

$$\frac{S_{\mathrm{Au}}}{S_{\mathrm{BB}}} = \frac{S_{GPL}}{S_{BB}}\frac{S_{Au}}{S_{GPL}} = \frac{\int R\,L(l,T_{\mathrm{Au}})\,dl}{\int R\,L(l,T_{\mathrm{BB}})\,dl}, \tag{1}$$

where $L(l,T)$ is the spectral radiance from the Planck radiance law, R is the relative spectral radiance responsivity, and S is the measured response. The relative spectral responsivities of the respective channels are shown in Fig. 2. The spectral responsivities of the modified PEP was measured in the

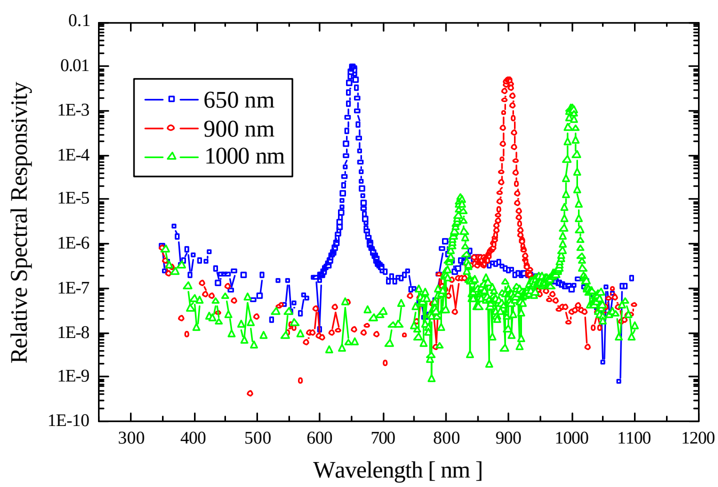

Figure 2: The relative spectral responsivity of the 650 nm, 900 nm, and 1000 nm measured in the NIST Spectral Comparator Facility.

NIST Spectral Comparator Facility (SCF)[7]. Only a part of the modified PEP was taken to the SCF for the responsivity measurements. The collections optics to the aperture stop was left in the RTCL and the part with the filter wheel and the temperature-stabilized detector was brought to the SCF for the measurements.

Figure 2 shows the measurement capability of the system needed for accurate determinations of radiance temperatures when attempting to compare spectral radiance ratios from blackbodies at widely different temperatures. The spectral responsivity of the pyrometer can be measured in the SCF with little degradation of the signal even in spectral regions where the signal is reduced by a factor of 10^{-5} from the peak of the responsivity. Typical filter transmittance measurements can follow the change in transmission to 10^{-5} albeit with signal-to-noise ratios quickly becoming close to 1. However, in the spectral wavelength range for the integrations used in Eq. 1, the spectral responsivities in the entire wavelength region from 350 nm to 1100 nm are important in the evaluation of the integral since the Si photodiode is sensitive throughout this wavelength region, and any increased uncertainties from the decreased signal-to-noise ratios can affect the radiance temperature calculations.

The radiance temperatures of the VTBB found using Eq. 1 are shown in Table 1. Initially, the modified PEP was used to measure the signals from the gold freezing-temperature blackbody, S_{Au} and then used to measure the signals from the gold-point lamp, S_{GPL}, at 650 nm, 900 nm, and at 1000 nm. The radiance temperatures of the VTBB are then determined using integrated radiance ratios to the GPBB using Eq. 1. Using the measured ratios of signals, the VTBB temperature in the Planck radiance law was iteratively changed and the integration was evaluated to determine a match in the radiance temperatures.

Table 1: The radiance temperatures measured using the 650 nm, 900 nm, and the 1000 nm channels of the modified PEP. The radiance temperatures were measured using the gold-point strip lamp, GPL, with its radiance temperatures determined using the GPBB.

Radiance Temperature [K]		
650 nm	**900 nm**	**1000 nm**
2771.68	2771.68	2771.40
2671.59	2671.60	2671.27
2571.87	2571.86	2571.55
2472.08	2472.11	2471.81
2372.02	2372.08	2371.73
2271.76	2271.81	2271.52
2171.31	2171.33	2171.05
2070.42	2070.35	2070.34
1972.78	1972.98	1972.45
1873.21	1873.23	1872.95
1773.04	1773.06	1772.83
1672.57	1672.39	1672.22
1572.57	1572.56	1572.32
1473.02	1473.07	1473.01
1373.45	1373.57	1373.47
1273.21	1273.11	1273.10
1172.24	1172.04	1171.98

4. ANALYSIS

The radiance temperature measurements of the VTBB have been analyzed using a constant emissivity or a gray-body emissivity model. The Planck radiance law with constant emissivity,

$$L(l,T) = \frac{e\, c_{1,L}}{n^2 l^5 \left(\exp\left(\frac{c_2}{n\, l\, T} \right) - 1 \right)}, \tag{2}$$

is used to derive the relationship between the emissivity, *e*, the thermodynamic temperature *T*, and the radiance temperature T_l. Although the temperatures were found using the full integrations, the analysis is done using the narrow-band approximations. Through manipulation of Eq. 2, the difference in radiance temperature measured at 650 nm to those measured at an arbitrary wavelength l_i is

$$\Delta T_{i,650} = \frac{c_2}{l_i} \frac{1}{\ln\left(1 + \frac{1}{e}\left(\exp\left(\frac{c_2}{l_i T} \right) - 1 \right) \right)} - \frac{c_2}{l_{650}} \frac{1}{\ln\left(1 + \frac{1}{e}\left(\exp\left(\frac{c_2}{l_{650} T} \right) - 1 \right) \right)}. \tag{3}$$

By plotting the differences of radiance temperatures at 900 nm and at 1000 nm from those found at 650 nm, the gray-body emissivity can be estimated. Figure 3 shows the plot of temperature

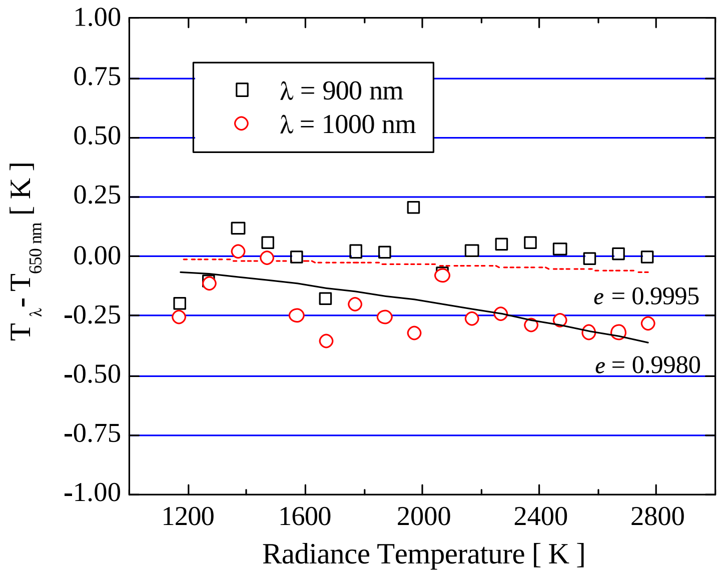

Figure 3: The radiance temperatures found using the 900 nm (open square) and the 1000 nm (open circle) channels of the multi-wavelength PEP plotted as differences from the 650 nm channel. The dotted line (solid) denotes the wavelength dependence of Eq. 3 of the 900 nm (1000 nm) channel with ε = 0.9995 (ε = 0.9980).

differences of the radiance temperatures found using the 900 nm and the 1000 nm bands from those found at 650 nm. Also plotted in Fig. 3 are the wavelength dependences of Eq. 3 for the 900 nm (1000 nm) band with a constant emissivity of $\varepsilon = 0.9995$ ($\varepsilon = 0.9980$).

5. DISCUSSION

The fits of the constant emissivity to the 900 nm and the 1000 nm data shown in Fig. 3, result in different values for the emissivity. The slight offset in temperatures between the two bands appears to be a systematic effect, lowering the radiance temperature measured by the 1000 nm channel by about 0.25 K. If the measurement of the relative spectral responsivity were incorrect, then a systematic offset in the measured radiance temperatures would occur. The SCF, where the spectral responsivities were measured, can calibrate radiometers with lower uncertainties in the spectral region from 400 nm to 920 nm, than at longer wavelengths. The importance of accurate spectral responsivity measurements were demonstrated when the inaccuracies of the spectral responsivities had a much more pronounced effect initially when the filter transmittances along with the convolved detector responsivities were used in the calculation of the radiance temperatures. The piece-parts approach led to almost 7 K differences between the radiance temperatures measured at 650 nm and the 900 nm.

6. SUMMARY

The emissivity of the VTBB used in the dissemination of the US national radiance temperature scale has been determined to be 0.9985 ± 0.0005 ($k = 1$) by comparison to the GPBB. The constant or gray-body emissivity was found using separate, independent determinations of radiance temperatures. The radiance temperatures of the VTBB were determined using spectral radiance ratios found with a pyrometer using narrow (10 nm) bandpass interference filters centered at 650 nm, 900 nm, and 1000 nm.

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REFERENCES

1. Gibson C.E., Tsai B.K., Parr A.C., *Radiance Temperature Calibrations (NIST Special Publication 250-43)*, Washington, 1998, US Government Printing Office.
2. Preston-Thomas H., *The ITS-90*, Metrologia, 1990, **27**, pp 3..10.
3. Bedford R.E., In *Theory and Practice of Radiation Thermometry*, (D.P. DeWitt and Gene Nutter, eds.), New York, John Wiley and Sons, 1988, p. 653.
4. Sapritsky V.I., Prokhorov A.V., *Appl. Opt.*, 1995, **34**, 5645-5652
5. Galal Yousef S., Sperfeld P., Metzdorf J., *Metrologia*, 2000, **37**, 365-368
6. Kostkowski H.J., Erminy D.E., Hattenburg A.T., *Adv. in Geophysics*, 1970, **14**, 111-127
7. Larason T.C., Bruce S.S., Parr A.C., *Spectroradiometric Detector Measurements (NIST Special Publication 250-41)*, Washington, 1998, US Government Printing Office.

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