A method of realizing spectral-radiance and irradiance scales based on comparison of synchrotron and high-temperature black-body radiation

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Abstract. Improvements in synchrotron radiation and high-temperature black-body sources will provide a method of realizing scales of spectral radiance and irradiance with uncertainties comparable with those provided by absolute cryogenic radiometers. This paper discusses planned improvements in the synchrotron radiation facility at the National Institute of Standards and Technology (NIST), and how these improvements can be exploited to accurately measure the temperature of a high-temperature black body developed at the All-Russian Research Institute for Optophysical Measurements (VNIIOFI), thus allowing substantial improvement in radiometric scales.

1. Introduction

Black bodies and charged-particle storage rings are the only two absolutely calculable sources of radiant flux. In principle, the spectral radiant power from each of these sources can be predicted to arbitrary precision based on fundamental physical laws and the measurement of a few simple parameters. Planckian theory completely determines spectral radiant exitance based on the temperature and effective emissivity of the radiating black body. The Schwinger theory of synchrotron radiation completely characterizes the spectral radiant power emitted from electron storage rings based only on the electron acceleration (dependent on the electron energy and local magnetic field) and the number of circulating electrons [1-3]. Recent intercomparisons between synchrotron and black-body radiation demonstrate agreement between Schwinger and Planckian theory to better than 1% commensurate with the relatively large measurement uncertainty [2-6]. Continuing improvements in storage-ring (SR) and high-temperature black-body (HTBB) sources will permit radiometric measurements at substantially reduced uncertainties and will open the way to new methods in the realization of radiometric scales.

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In this paper we outline existing performance and planned improvements in two specific sources: the HTBB series developed at the All-Russian Research Institute for Optophysical Measurements (VNIIOFI) and the electron storage ring SURF II at the National Institute of Standards and Technology (NIST). The improved HTBB source, capable of operation at up to 3200 K, can be used to substantially reduce the uncertainties in the scales of spectral radiance and irradiance, but only if the HTBB temperature can be accurately determined. Accurate measurement of such high temperatures is only possible radiometrically, and we describe a method to measure the HTBB temperature through the ratio of the spectral irradiance of the SR and HTBB sources measured at two wavelengths. Exploiting improvements in the SR source, this method will allow the temperature of the HTBB to be determined to about 0,4 K uncertainty or better near 2800 K (3 σ), commensurate with realizing scales of spectral radiance and irradiance to a few tenths of one percent uncertainty over the visible spectrum. The HTBB temperature will also be determined using filter-detector radiometers calibrated against the High-Accuracy Cryogenic Radiometer (HACR) at the NIST [7, 8]. The SR source-based and detector-based determinations will be complementary.

The improved HTBB and SR sources will allow completely independent realization of radiometric scales at reduced uncertainty to probe for possible unrecognized systematic measurement uncertainties. Agreement, within the expected uncertainties, between detector-based radiometric scales (tied to high-accuracy cryogenic radiometry) and source-based scales (tied to the fundamental physics of HTBB and SR sources) improves confidence in the scales and demonstrates how precisely the scales can be transferred in practice from the primary standards. Planned improvements in the SR source will also provide the means to unify and extend disparate radiometric scales into a single set of scales, potentially covering the spectral range from soft x-rays (near 1 nm) to the far-infrared (beyond 10 μm).

2. Measurement of HTBB temperature using radiometric methods tied to synchrotron radiation

The principal uncertainty in the determination of the spectral radiance of the HTBB is the uncertainty in the measurement of the radiance temperature of the emitting cavity. Other uncertainties – including deviations of HTBB spectral emissivity from unity, fluctuations in HTBB temperature, diffraction at apertures in the measurement system and uncertainty in measurement wavelengths and spectral bandpasses – are typically much smaller. Only a radiometric determination of the cavity temperature is possible at the higher operating temperatures (near 3000 K). One method of measuring the HTBB temperature is to compare the ratios of the HTBB irradiance to the SR irradiance at two wavelengths. This method determines the HTBB temperature based only on relative irradiance measurements.

Consider two detectors (such as filter radiometers) or a spectroradiometer measuring spectral irradiance in two different narrow spectral bandpasses centred at wavelengths λ_1 and λ_2. When measuring the HTBB irradiance, the ratio of the signals at the two wavelengths will be (assuming the cavity spectral emissivity is identical at both wavelengths)

$$\frac{S_{\mathrm{BB}}(\lambda_2)}{S_{\mathrm{BB}}(\lambda_1)} = \frac{\displaystyle\int \frac{Q_2(\lambda)\,\mathrm{d}\lambda}{\lambda^5\left[\exp\left(\dfrac{c_2}{\lambda T}\right)-1\right]}}{\displaystyle\int \frac{Q_1(\lambda)\,\mathrm{d}\lambda}{\lambda^5\left[\exp\left(\dfrac{c_2}{\lambda T}\right)-1\right]}}, \tag{1}$$

where $S_{\mathrm{BB}}(\lambda)$ is the irradiance signal at wavelength λ, $Q(\lambda)$ is the detector spectral responsivity, c_2 is the second radiation constant, and T is the temperature of the HTBB. For simplicity, the measurement geometry is assumed to be identical in each case so the angular dependence of irradiation does not affect the irradiance ratio. The integration extends over the spectral bandpass of each detector. In the limit that the spectral bandpass of the detector approaches zero, and using the Wien approximation, (1) reduces to

$$\frac{S_{\mathrm{BB}}(\lambda_2)}{S_{\mathrm{BB}}(\lambda_1)} = \left(\frac{\lambda_1}{\lambda_2}\right)^5 \frac{Q_2(\lambda_2)}{Q_1(\lambda_1)} \frac{\exp\left(\dfrac{c_2}{\lambda_1 T}\right)}{\exp\left(\dfrac{c_2}{\lambda_2 T}\right)}. \tag{2}$$

Using the same two detectors to measure the relative spectral irradiance of the SR source, the ratio of the signals S_{SR} is

$$\frac{S_{\mathrm{SR}}(\lambda_2)}{S_{\mathrm{SR}}(\lambda_1)} = \frac{\displaystyle\int Q_2(\lambda)\,E(\lambda,\psi)\,\mathrm{d}\lambda\,\mathrm{d}\psi}{\displaystyle\int Q_1(\lambda)\,E(\lambda,\psi)\,\mathrm{d}\lambda\,\mathrm{d}\psi}, \tag{3}$$

where $E(\lambda,\psi)$ is the spectral-irradiance distribution of the SR depending on wavelength λ and angle ψ normal to the electron orbital plane. Again, the measurement geometry is assumed to be identical for each detector (although not necessarily the same as for the black-body irradiance measurements). Assuming narrow spectral bandwidth as before, (3) reduces to

$$\frac{S_{\mathrm{SR}}(\lambda_2)}{S_{\mathrm{SR}}(\lambda_1)} = \frac{Q_2(\lambda_2)\displaystyle\int E(\lambda_2,\psi)\,\mathrm{d}\psi}{Q_1(\lambda_1)\displaystyle\int E(\lambda_1,\psi)\,\mathrm{d}\psi}. \tag{4}$$

For wavelengths much longer than the critical wavelength (the wavelength dividing the SR power spectrum into equal parts) the narrowband irradiance ratio asymptotically approaches

$$\frac{\displaystyle\int E(\lambda_2,\psi)\,\mathrm{d}\psi}{\displaystyle\int E(\lambda_1,\psi)\,\mathrm{d}\psi} \approx \left(\frac{\lambda_2}{\lambda_1}\right)^{-\frac{7}{3}}, \tag{5}$$

when the irradiated target subtends an angle large enough to collect essentially all the highly collimated radiation emitted by the relativistic electrons in the direction normal to the orbital plane. The exponent in (5) will deviate slightly from $-\frac{7}{3}$ depending on the wavelengths used, but the correct exponent can be determined from the storage-ring parameters (electron energy and magnetic field).

The ratio $A(\lambda_1,\lambda_2,T)$ of the SR irradiances (4) to the HTBB irradiances (2), using (5), is

$$A(\lambda_1,\lambda_2,T) = \left(\frac{\lambda_2}{\lambda_1}\right)^{\frac{8}{3}} \frac{\exp\left(\dfrac{c_2}{\lambda_2 T}\right)}{\exp\left(\dfrac{c_2}{\lambda_1 T}\right)}. \tag{6}$$

Equation (6) can be solved for the HTBB temperature T:

$$T = \frac{c_2\left(\dfrac{1}{\lambda_2}-\dfrac{1}{\lambda_1}\right)}{\ln\left[A(\lambda_1,\lambda_2,T)\left(\dfrac{\lambda_1}{\lambda_2}\right)^{\frac{8}{3}}\right]}. \tag{7}$$

The exponent in the logarithm deviates slightly from $\frac{8}{3}$ in a predictable way depending on the wavelengths used and the angular subtense of the detectors.

This analysis shows that the HTBB temperature can be determined through measurements at only two wavelengths, although it is of course desirable to make intercomparison at several different wavelengths to avoid unrecognized systematic error. The temperature determination is completely independent of the absolute spectral responsivity of the detectors used. Only the relative spectral radiant power of the HTBB and SR sources need be measured.

3. Uncertainties in HTBB temperature determination

From (7), the fractional uncertainty $\Delta T/T$ in the HTBB temperature can be determined from

$$\left(\frac{\Delta T}{T}\right)^2 = \left[\frac{T\lambda_1\lambda_2}{c_2\left(\lambda_1-\lambda_2\right)}\,\frac{\Delta A}{A}\right]^2 + \left[\frac{\lambda_2\left(c_2-\frac{8}{3}T\lambda_1\right)}{c_2\left(\lambda_1-\lambda_2\right)}\,\frac{\Delta\lambda_1}{\lambda_1}\right]^2 + \left[\frac{\lambda_1\left(\frac{8}{3}T\lambda_2-c_2\right)}{c_2\left(\lambda_1-\lambda_2\right)}\,\frac{\Delta\lambda_2}{\lambda_2}\right]^2, \qquad (8)$$

where the independent uncertainties have been combined in quadrature. For a realistic measurement in which $T=2800$ K, $\lambda_1=300$ nm, $\lambda_2=900$ nm, $\Delta A/A=0{,}1\,\%$, and $\Delta\lambda_1/\lambda_1=\Delta\lambda_2/\lambda_2=0{,}01\,\%$, the temperature uncertainty is approximately $\Delta T=0{,}4$ K. (All uncertainties are 3 σ estimates).

This analysis neglects the uncertainty in the SR irradiance reaching the detectors. The SR irradiance uncertainty results from both uncertainties in the relevant storage-ring parameters (such as electron energy and local magnetic field) that determine the spectral and spatial distribution of radiation reaching the detector, and from practical uncertainties in the intercomparison of SR and HTBB irradiation. We consider here only the effects of uncertainty in the fundamental storage-ring parameters which completely determine the spectral and spatial distribution of SR synchrotron radiation.

The exponent in the SR irradiance ratio power law (5) differs slightly from $-\frac{7}{3}$ depending on the two measurement wavelengths chosen and on the alignment and angular subtense of the detector relative to the electron orbital plane. The exponent asymptotically approaches $-\frac{7}{3}$ as the wavelengths become much longer than the critical wavelength (approximately 17,4 nm for SURF II) and as the detector angular subtense is sufficienty large for all the radiation emitted normal to the orbital plane to be collected. However, any practical comparison of HTBB and SR irradiance would use detectors sensitive to wavelengths near the visible range and collecting only a limited portion of the vertical angular divergence of the synchrotron radiation.

If the storage ring parameters are accurately known, the effects of limited detector subtense and synchrotron radiation spectral distribution can be modelled and the HTBB temperature inferred from expressions similar to (7) (using the appropriate exponent differing somewhat from $\frac{8}{3}$). Uncertainties in the SR parameters (particularly electron energy and local orbital radius) result in uncertainty in the exponent and thus uncertainty in the HTBB temperature. Using the wavelengths in the previous example, a 1 % uncertainty in the electron energy results in an uncertainty of about 0,3 K to 0,4 K in the HTBB temperature depending on the detector angular subtense. This uncertainty, due solely to uncertainty in the storage-ring parameters, is comparable to the uncertainty of 0,4 K from (8) which considered only the irradiance ratio measurement uncertainties. Reducing the SR parameter uncertainty would substantially reduce the overall uncertainty in the HTBB temperature determination.

The SR irradiance uncertainty contribution to the HTBB temperature measurement will be dramatically reduced through the planned upgrade of the NIST storage ring to SURF III. The principal improvement will be a substantially more uniform magnetic field resulting from replacement of the existing dipole magnet pole pieces. As a by-product, the maximum electron energy should increase to about 375 MeV. The improved magnetic-field uniformity will result in reduction of the uncertainties in electron energy and effective orbital radius to order 0,1 % or better, dramatically decreasing the SR irradiance uncertainty contribution to the HTBB temperature determination. The higher electron energy further decreases the HTBB temperature uncertainty at wavelengths in the 300 nm to 900 nm range. These improvements will render the SR irradiance contribution to the HTBB temperature determination negligible compared with the other measurement uncertainties (8). A radiometric temperature measurement with an uncertainty of about 0,4 K near 2800 K (3 σ) would represent an improvement by more than a factor of three over the current uncertainty in NIST radiation temperature scales [9].

There are additional concerns over the comparison of SR and HTBB irradiances, such as the polarization of SR radiation compared to the randomly polarized HTBB radiation and the temporal decay of SR irradiance intensity as electrons are scattered out of the orbital path (principally by electron-electron Touscheck scattering). It is expected that these concerns can be addressed relatively easily and should make a negligible contribution to the HTBB temperature uncertainty.

The principal conclusion is that the HTBB temperature measurement and realization of spectral radiance and irradiance scales can be made with significantly reduced uncertainty through radiometric comparison of HTBB and SR irradiances at two or more wavelengths. Planned improvements to the NIST SURF II electron storage ring will ensure that the HTBB temperature and radiometric scales can be realized with the least possible uncertainty.

4. High-temperature black-body source

High-temperature black bodies with excellent temperature uniformity over relatively large apertures have been developed at the VNIIOFI [10]. These sources are especially well-suited for use in establishing improved spectral-irradiance scales [7, 11]. The HTBB designated type BB22P with a resistively heated graphite cavity has been shown to work well at temperatures up to 2900 K. A new-generation HTBB (BB3200pg) with a pyrolytic graphite cavity for higher-temperature operation is currently under development. It is designed for operation at up to 3200 K, which will significantly improve the accuracy of UV spectral-irradiance measurements. Both black bodies are designed for operation without any window to optimize radiometric accuracy. Special design and materials permit long-term high-temperature operation with the cavity aperture open to the environment and only a modest flow of argon gas to prevent oxidation of the cavity. Table 1 summarizes the important characteristics of the two HTBB sources.

Table 1. High-temperature black-body specifications.

Parameter	BB22P	BB3200pg (planned)
Maximum operating temperature	2900 K to 3000 K	3200 K to 3300 K
Typical working temperature	2600 K to 2800 K	2800 K to 3000 K
Cavity material	Graphite	Pyrolytic graphite
Inner-cavity diameter	22 mm	40 mm
Cavity-aperture diameter	8 mm	16 mm
Normal effective emissivity	≥ 0,999	≥ 0,999
Spatial uniformity	0,05 %	0,05 %
Maximum current	400 A	600 A
Typical lifetime	500 hours at 2800 K	2000 hours at 2800 K 100 hours at 3200 K

5. Synchrotron source

The Synchrotron Ultraviolet Radiation Facility (SURF) radiation sources at NIST have evolved from SURF I to the current SURF II [12] with plans under way for the upgrade to SURF III. The 180 MeV electron synchrotron SURF I source was commissioned in 1961. The synchrotron was converted to the 240 MeV dc storage ring SURF II in 1974. Continued modifications to SURF II have increased the maximum electron energy to 300 MeV with stored currents approaching 400 mA. The principal goal for the SURF III upgrade is to enhance its effectiveness as a national radiometric source for the soft x-ray through far-infrared spectral regions. Table 2 summarizes the characteristics of the existing SURF II and the planned SURF III.

Table 2. SURF II/III parameters.

Parameter	SURF II (current)	SURF III (planned)
Critical wavelength	17,4 nm at 300 MeV	≤ 10,3 nm at ≥ 375 MeV
Typical lifetime	2,5 hours at 200 mA	Comparable or longer
Minimum beam size:		
vertical (FWHM)	0,1 mm	Smaller
radial (FWHM)	1,5 mm	Comparable
Energy range	10 MeV to 300 MeV	10 MeV to 375+ MeV
Typical operating energy	284 MeV	~ 375 MeV
Maximum electron-beam current	390 mA	Comparable
Typical electron-beam current	> 200 mA	Comparable
Magnet structure	Single, weak focus	Single, weak focus
Straight sections	None	None
Maximum bending field	1,2 T	~ 1,4 T
Field index, n	0,59	~ 0,59
RF (twice orbital frequency)	113,8 MHz	~ 99 MHz
Number of bunches	2	2 or more
Bunch length	~ 1 ns	~ 1 ns

6. Conclusion

NIST is beginning the upgrade of the Synchrotron Ultraviolet Radiation Facility to provide substantially improved radiometric measurements. As an example of improved measurements possible with SURF III, a detailed analysis is presented of a high-precision method to measure the temperature of a high-temperature black body based on intercomparison of the black body, and synchrotron radiation at two or more wavelengths. Such measurements will lead to reduction of uncertainty in the scales of spectral radiance and irradiance in the ultraviolet through near-infrared regions. High-accuracy comparison of radiometric scales realized through completely independent methods, such as absolute cryogenic radiometry and the synchrotron-black-body method described here, are vital to improve confidence that no unrecognized systematic errors have degraded the measurements and to demonstrate how accurately radiometric scales can be transferred.

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