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Advancements in NRC's Primary Spectral Irradiance Scale Realization

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Abstract. The National Research Council (NRC) of Canada has been working to establish new facilities and to improve measurement capabilities traceable to the International System of Units (SI units) in optical radiometry. The NRC primary spectral irradiance scale has transitioned from a detector-based approach in the range of 700 nm to 1600 nm to a detector and source-based realization from 250 nm to 2500 nm. A high temperature blackbody (HTBB) acts as the primary light source for the calibration of 1000 W FEL spectral irradiance standard lamps. The thermodynamic temperature of the HTBB is determined using an NRC-designed wide-band filter radiometer, with spectral responsivity SI-traceable to the NRC optical power scale. This new facility has significantly improved measurement uncertainties compared to the previous NRC spectral irradiance scale.

1. Introduction

Spectral irradiance standard lamps are used in many applications including the calibration of other light sources and optical systems. For example, spectral irradiance is implemented in the determination of the correlated colour temperature of a light source and in the calibration of instruments used for light and optical properties characterization such as spectroradiometers and spectrophotometers. Over the past decade, the National Research Council (NRC) Canada has been working to establish a new facility for a source and detector-based primary realization of spectral irradiance [1]. The previous NRC spectral irradiance scale from 250 nm to 2500 nm was comprised of a combination of three different SI-traceability routes in different wavelength regions. From 300 nm to 700 nm, the scale was maintained on 500 W quartz-halogen lamps calibrated according to the NRC-CIE World Mean of 1975 scale [2]. From 250 nm to 300 nm and from 1600 nm to 2500 nm, the scale was SI-traceable to 1000 W FEL lamps purchased from the National Institute of Standards and Technology in the United States. In the near infrared spectral range of 700 nm to 1600 nm, NRC realized a detector-based scale using interference filters and absolute radiometers to calibrate tungsten-halogen lamps [3]. Now, NRC has a facility equipped with a high temperature blackbody (HTBB) that is implemented as a primary standard radiometric light source in spectral irradiance measurements. The thermodynamic temperature of the HTBB is determined using a wide-band filter radiometer [4], which has a spectral responsivity calibration SI-traceable to the NRC optical power scale through the NRC absolute cryogenic radiometer

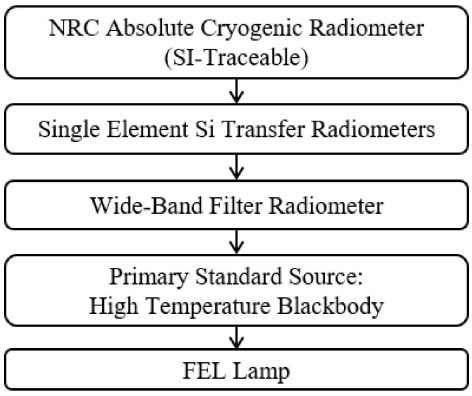

Figure 1. NRC optical radiation traceability chain for FEL spectral irradiance standard lamps.

[5, 6], giving a source and detector-based spectral irradiance scale realization (Figure 1). The design of the NRC spectral irradiance facility, measurement procedure, and uncertainty analysis are presented.

2. Spectral irradiance facility

A schematic diagram of the NRC primary spectral irradiance measurement facility is shown in Figure 2. Two 1000 W FEL lamp stations and the HTBB (model BB3500M VNIIOFI, Russia) are installed on separate optical tables. The monochromator system (1 metre GCS McPherson Model 2051), filter radiometer, and a linear pyrometer (LP5, KE-Technologie) are installed on a third optical table equipped with a rail and lead screw system as well as a linear encoder which facilitates two metres of translation. A prism pre-disperser and integrating sphere with a 6 mm input port are mounted to the monochromator input. To reduce stray light, a light-tight box with a 3 cm entrance aperture is installed around the integrating sphere/predisperser input assembly. Inside the light-tight box, a beam blocker on a motorized flip mount is used to block the incident light for dark signal measurements. A HeNe laser and beam splitter are used for the optical alignment of the filter radiometer and HTBB, the monochromator entrance aperture and the HTBB, and the FEL alignment jig and monochromator entrance aperture. A custom software program enables the computer controlled positioning of the different light sources and detectors and for data collection. For spectral data collection, to complete the range of 250 nm to 2500 nm, the single grating monochromator is utilized with various combinations of two 600 groove/mm diffraction gratings and three photodetectors: a photomultiplier tube (PMT), a single element Si detector, or an InSb detector (Table 1).

During measurements, the monochromator diffraction gratings and photodetectors are changed manually with subsequent verification of wavelength calibration and detector alignment. Spectral data from the HTBB and FEL standard lamps are collected using the same grating, photodetector, and transimpedance amplifier combinations for each spectral range (e.g. 400 nm to 1100 nm).

Each FEL lamp station is equipped with translation, rotation, and goniometer stages for alignment of the lamps using FEL alignment jigs and the HeNe laser. Stray light from the lamps is minimized by an enclosure with two black side panels and a front panel with a 7.5 cm aperture, as well as conical light traps installed behind the lamps to capture the optical radiation emitted in the backward direction. The lamp stations are each connected to a DC power supply (Agilent Technologies N6977A) and calibrated shunt resistor.

The HTBB has a water-cooled aperture at the output. A beam blocker on a motorized flip mount, placed between the filter radiometer and water-cooled HTBB aperture, is used to perform dark signal measurements. The linear pyrometer is used to monitor the temperature stability of the HTBB before the start of data collection, but is not used in the thermodynamic temperature determination of the HTBB.

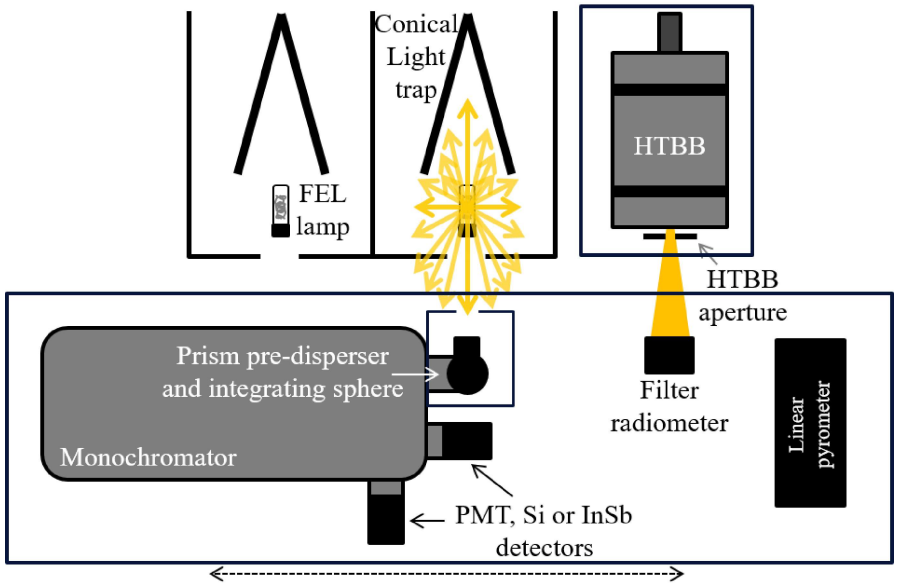

Figure 2. Simplified diagram of the NRC primary spectral irradiance facility.

Table 1. Grating and detector types for spectral measurements.

Wavelength range	Detector	Grating blaze
250 nm - 380 nm	PMT	400 nm
400 nm - 1100 nm	Si	400 nm
1300 nm - 2500 nm	InSb	2700 nm

3. Spectral irradiance measurement

The spectral irradiance of an FEL standard lamp, $E_{\lambda,\,\mathrm{FEL}}$, at a wavelength λ, is determined using the spectral irradiance of the HTBB, $E_{\lambda,\,\mathrm{HTBB}}$, and the ratio of the measured FEL lamp and HTBB spectra, $S_{\lambda,\mathrm{FEL}}$ and $S_{\lambda,\mathrm{HTBB}}$, from the monochromator system:

$$E_{\lambda,\mathrm{FEL}} = E_{\lambda,\mathrm{HTBB}}\frac{S_{\lambda,\mathrm{FEL}}}{S_{\lambda,\mathrm{HTBB}}}. \qquad (1)$$

$E_{\lambda,\,\mathrm{HTBB}}$ depends on the thermodynamic temperature of the HTBB, T, as well as several geometric factors which convert the spectral radiance of the HTBB to its spectral irradiance at the filter radiometer input aperture:

$$E_{\lambda,\mathrm{HTBB}} = \left(\frac{\pi r_{\mathrm{HTBB}}^2}{(d^2+r_{\mathrm{FR}}^2+r_{\mathrm{HTBB}}^2)}\right) \times \left(\frac{2\varepsilon hc^2}{\lambda^5 n^2 e^{hc/n\lambda kT}-1}\right) \qquad (2)$$

where r_{HTBB} and r_{FR} are the radii of the HTBB and filter radiometer precision apertures, d is the distance between these two apertures, ε is the emissivity of the HTBB, h is the Planck constant, c is the speed of light, n is the refractive index of air, and k is the Boltzmann constant. In the NRC spectral irradiance facility, the distances of the HTBB and filter radiometer apertures, the HTBB and monochromator aperture, and the FEL lamps and monochromator aperture are set using a calibrated length bar (d=499.945 mm). During spectral irradiance measurements, the HTBB is operated at a temperature of 2950 K. First, T is determined by measuring the signal from the HTBB with the wide-band filter radiometer. The monochromator system is then employed to collect spectral data from the HTBB output ($S_{\lambda,\mathrm{HTBB}}$). T is then measured a second time with the filter radiometer to confirm the stability of the

HTBB temperature. Spectral data from an FEL lamp ($S_{\lambda,\mathrm{FEL}}$) is then collected using the monochromator system.

4. Measurement uncertainties

The uncertainty components in the determination of T, $E_{\lambda,\mathrm{HTBB}}$, the spectral irradiance scale realization, as well as the lamp measurement characteristics have been incorporated into the uncertainty budget. The estimation of uncertainties have been analysed according to the Guide to the expression of uncertainty in measurement (GUM) [7].

4.1. Uncertainties in HTBB spectral irradiance

For the determination of T and $E_{\lambda,\mathrm{HTBB}}$, the uncertainties in the spectral responsivity calibration of the filter radiometer, r_{FR}, d, r_{HTBB}, HTBB radiance uniformity, ε, and n [8] are considered. A sensitivity coefficient is used to convert the relative value of each uncertainty component to an uncertainty in T [9]. The resulting effect on $E_{\lambda,\mathrm{FEL}}$ is determined by calculating $E_{\lambda,\mathrm{HTBB}}$ at the input aperture of the wide-band filter radiometer using values of T with the incorporated temperature uncertainties (Figure 3). The uncertainty components related to the geometric factors, ε, and n in equation 2 are included in the determination of T and are not accounted for a second time in the calculation of the uncertainty in $E_{\lambda,\mathrm{HTBB}}$.

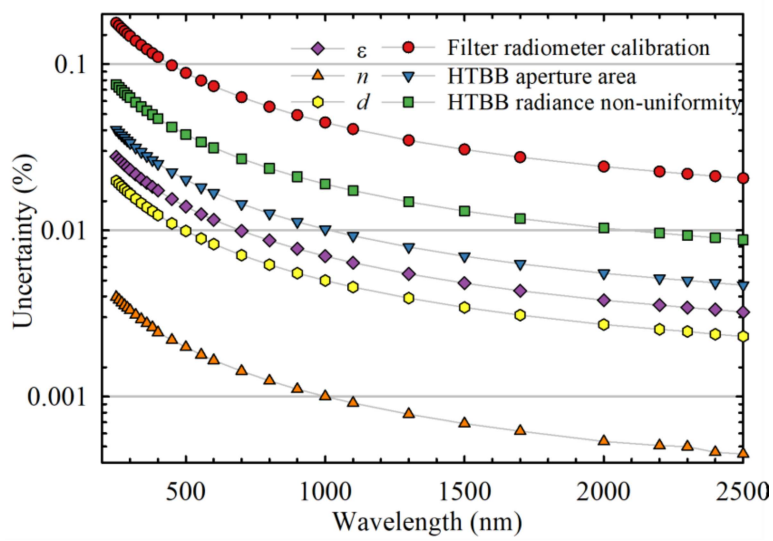

Figure 3. Uncertainties in spectral irradiance $E_{\lambda,\mathrm{HTBB}}$ due to uncertainties in the components of the HTBB temperature measurement (k=1).

4.2. Uncertainties in spectral irradiance scale realization

Further uncertainty components for the spectral irradiance scale realization are the uncertainties in the FEL lamp distance, the monochromator wavelength calibration, the HTBB temperature stability, the repeatability of the measurement of the FEL lamp current, and the repeatability of the filter radiometer and monochromator alignment positioning. The uncertainty due to the lamp distance measurement was calculated using equation 3, where the uncertainty of the length bar (17 µm) and the repeatability of the lamp translation stage micrometer (0.05 mm) were accounted for, and was found to be 0.021%.

$$E_b = E_a(d_a/d_b)^2 \qquad (3)$$

The same calibrated length bar and micrometers with the same resolution were used for the measurements of the lamp distance to the monochromator input and of the filter radiometer to the HTBB aperture.

The uncertainty due to the uncertainty in the monochromator wavelength calibration was calculated using equation 4:

$$u\big(S(\lambda)\big) = \frac{d\left(\frac{S_{\lambda,\mathrm{FEL}}}{S_{\lambda,\mathrm{HTBB}}}\right)}{d\lambda} \times u(\lambda) \qquad (4)$$

where $u(\lambda)$ is the residual wavelength uncertainty obtained after wavelength calibration correction curves have been applied to the monochromator system (±0.1 nm). The resulting effect of the monochromator wavelength uncertainty on $E_{\lambda,\mathrm{FEL}}$ is shown in Figure 4. The repeatability of the monochromator wavelength is better than 0.1 nm, which has a negligible effect.

The temperature stability of the HTBB was calculated from the difference between the first and second measurements of T and was found to be less than 0.2 K. This drift is evaluated as an uncertainty using a rectangular distribution and equations 1 and 2 were used to determine the effect on $E_{\lambda,\mathrm{FEL}}$.

A rectangular distribution is used to convert the repeatability of the FEL lamp current measurement to a standard uncertainty. The FEL lamp current is continuously monitored throughout the measurements. The calibration of the digital multimeters and shunt resistors for both lamp stations, as well as the repeatability of the lamp current measurements have a combined uncertainty of 572 µA. To convert the uncertainty in lamp current, I, to an uncertainty in lamp spectral irradiance, the lamp output radiation power, P, is taken to be proportional to the input electrical power ($\propto I^2$), and $E_{\lambda,\mathrm{FEL}} \propto P$. If we assume that the optical radiation output of the lamp may be approximated by Planck's law, by combining the differentiated expressions of the Stefan-Boltzmann law $P = \sigma {T_{\mathrm{FEL}}}^4$, and an expression for electrical power $P = I^2 R$, where σ is the Stefan-Boltzmann constant and T_{FEL} is the distribution temperature of the FEL lamp [10], the change in temperature can be written as:

$$dT_{FEL} = \frac{T_{FEL}\, dI}{2I}. \qquad (5)$$

This change in temperature, dT_{FEL}, was calculated using the combined uncertainty of the lamp current measurement, and was then applied to T_{FEL} to evaluate the effect on spectral irradiance of the FEL lamp.

The repeatability of the wide-band filter radiometer and monochromator positioning with the rail and lead screw system and linear encoder is ±5 µm and is considered to be negligible.

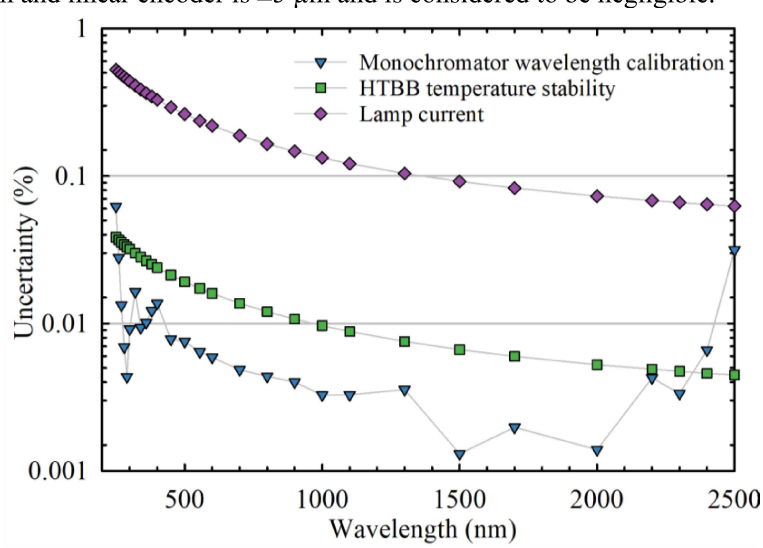

Figure 4. Uncertainty components of the scale realization (k=1).

4.2.1. FEL lamp measurement uncertainties

The uncertainty due to the lamp measurement repeatability is determined using the standard deviation of the mean calculated from a set of three consecutive measurements using the monochromator system. For lamp measurement reproducibility, the uncertainty is determined by the standard deviation of the mean calculated from the results of three independent measurements after lamp re-alignment.

4.3. Improvements in scale realization uncertainties

The implementation of the HTBB as a primary standard light source has enabled a continuous spectral irradiance scale realization from 250 nm to 2500 nm at NRC. Previous SI-traceability was accomplished through three separate traceability routes as shown in Figure 5, where the uncertainties of the new NRC source and detector-based scales are the combined uncertainty components from Figures 3 and 4. The new NRC scale shows great improvement in measurement uncertainties. The total uncertainty for the calibration of FEL standard lamps depends on the uncertainties in the determination of the temperature T of the HTBB, the transfer of the spectral irradiance of the HTBB to the spectral irradiance of the FEL lamps (scale realization), as well as the FEL lamp repeatability and stability. Figure 6 shows spectral irradiance data and uncertainties for the HTBB at 2950 K and for a 1000 W FEL lamp. The large increase in the uncertainty in the spectral irradiance of the FEL lamps ($u(E_{\lambda,\mathrm{FEL}})$) above 1200 nm is due to the noise in the signal of the InSb detector. To further reduce lamp measurement uncertainties, an extended InGaAs detector will be installed in the facility to replace the InSb detector from 1200 nm - 2500 nm. Although other National Metrology Institutes [11] have published smaller measurement uncertainties than those obtained in this work, our initial goal here is to have an independent scale realization with SI-traceability through measurements performed solely at NRC Canada.

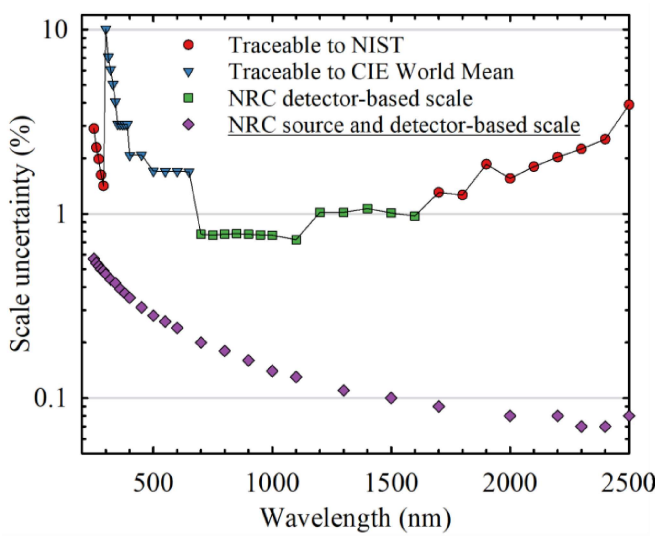

Figure 5. NRC spectral irradiance scale uncertainties, excluding FEL lamp measurement uncertainties (k=1).

5. Conclusions

We have established at NRC a primary, SI-traceable, spectral irradiance scale in the 250 nm to 2500 nm wavelength range. This source-and-detector scale is based upon the transfer of the spectral irradiance of an HTBB to the FEL spectral irradiance standard lamps. The spectral irradiance of the HTBB is determined from the spectral radiance of the HTBB, whose operating temperature has been determined from irradiance measurements with a wide-band filter radiometer, whose measured spectral responsivity is SI-traceable to the NRC optical power scale. We have determined the relative standard measurement uncertainty for the spectral irradiance of the HTBB standard radiometric source to be less than 0.2%

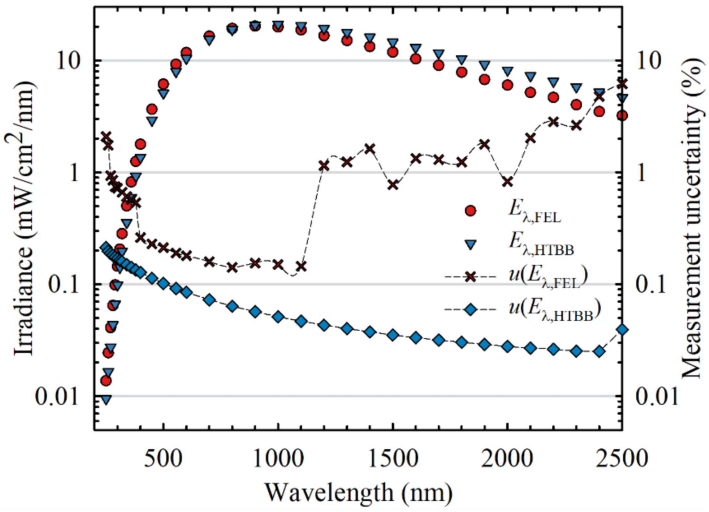

Figure 6. Measured 1000 W FEL lamp and HTBB (2950 K) irradiance and uncertainties (u) (k=1).

(0.4% expanded at k=2) across this wavelength range. The realization of the spectral irradiance scale onto the FEL spectral irradiance standard lamps had an associated relative standard uncertainty of better than 0.3% in the visible wavelength range, but was limited by detector signal noise, particularly above 1200 nm in the IR. We plan to reduce these uncertainties by implementing an alternative photodetector in the infrared spectral region.

This new scale will replace the former NRC spectral irradiance scale that was dependent upon several routes for its SI traceability. The uniformity of the scale across the wavelength range and the reduction in the scale uncertainties present a significant improvement upon our previous scale.

6. Disclaimer

The commercial equipment identified in this paper are for informative purposes only. Such identification does not imply recommendation or endorsement by NRC, nor does it imply that the equipment is necessarily the best available for the purpose.

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