Spectral irradiance scale realization and uncertainty analysis based on a 14 mm diameter WC–C fixed point blackbody from 250 nm to 2500 nm

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Abstract
Spectral irradiance scale in the wavelength range from 250 nm to 2500 nm was realized at National Institute of Metrology on the basis of a large area tungsten carbide–carbon (WC–C) high temperature fixed point blackbody, which is composed of a 14 mm diameter WC–C fixed point cell and a variable temperature blackbody BB3500MP as a furnace. A series of 1000 W FEL tungsten halogen lamps were used as transfer standards. The new spectral irradiance scale was compared with the scale based on a variable-temperature blackbody BB3500M, and the divergence between these two methods varied from −0.66% to 0.79% from 280 nm to 2100 nm. The measurement uncertainty of spectral irradiance scale based on fixed-point blackbody was analyzed, and the expanded uncertainty was estimated as 3.9% at 250 nm, 1.4% at 280 nm, 0.43% at 400 nm, 0.27% at 800 nm, 0.25% at 1000 nm, 0.62% at 1500 nm, 0.76% at 2000 nm, and 2.4% at 2500 nm respectively. In the range from 300 nm to 1000 nm the fixed-point scale was improved obviously: the uncertainty decreased by more than 25% compared to the uncertainty based on the variable temperature blackbody. Below 300 nm, the uncertainty became higher because the signal to noise ratio was poor. Above 1100 nm, the contribution of temperature measurement to the uncertainty of spectral irradiance decreases, therefore the uncertainties of two methods are almost at the same level. The fixed-point blackbody was also used to realize the correlated colour temperature and distribution temperature of a tungsten filament lamp, the deviation from the variable temperature blackbody method was −0.5 K and −2.9 K, respectively.

Keywords: spectral irradiance, fixed point blackbody, variable temperature blackbody, uncertainty budget, WC-C fixed point

(Some figures may appear in colour only in the online journal)
1. Introduction

Spectral irradiance is a basic radiometric quantity, and one of the six key-comparisons quantities selected by the Consultative Committee for Photometry and Radiometry of International Committee for Weights and Measures. Spectral irradiance is widely used in the fields of climate change monitoring [1], aerospace engineering [2], remote sensing [3] and other fields etc. Accurate measurement of spectral irradiance is required in many national programs and industrial applications.

Realisation of spectral irradiance scale is usually based on a high temperature blackbody. In order to improve the accuracy of high temperature measurement, a series of high temperature fixed-point (HTFP) blackbodies were developed. For pure metal fixed-point blackbodies, the Cu fixed point has the highest temperature of 1357.77 K. In 1999, Yamada (National Metrology Institute of Japan, NMIJ) developed the metal–carbon (M–C) HTFPs. The eutectic materials have the phase transformation characteristics similar to the pure metals, and the temperature plateaus are almost unchanged in the process of phase transformation [4, 5]. Subsequently, Yamada successfully developed the metal carbide–carbon (MC–C) HTFPs with higher temperatures of phase-transition plateaus [6, 7]. Several national metrology institutes were focused on further development of HTFPs. All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI) has successfully developed a series of large-area HTFPs and large-area high temperature blackbody sources [8, 9]. National Institute of Metrology (NIM) took part in the international cooperation and independently manufactured a batch of high-quality M–C and MC–C HTFPs [10, 11].

WC–C fixed point is suitable for spectral irradiance application because its melting temperature, 3020.6 K, is close to the distribution temperature of tungsten halogen lamps. Another important advantage of WC–C is the fact that its thermodynamic temperature value will be soon updated within the international project ‘realising the redefined kelvin’ (Real-K) [12], which will make this fixed point available for the mise en pratique of the kelvin and link the spectral irradiance scale with the newly defined kelvin. The 3 mm diameter WC–C HTFP blackbodies are generally used in radiation thermometry [13, 14], or in radiometry for traceability to temperature scale [15, 16]. After development and investigation of small WC–C cells with cavity diameters of 3 mm and 5 mm [17, 18], VNIIOFI developed a large area fixed-point cell blackbody with the cavity diameter of 14 mm [19]. The large-area cell has longer phase-transition melting plateau and relatively high radiation flux compared to a small-area HTFP cell of the same type (figure 1).

In order to meet the increasing needs for high accuracy calibration of spectral irradiance in various fields in China, a large-area WC–C high temperature fixed-point blackbody system was set up at NIM, which is composed of a 14 mm diameter WC–C cell and a BB3500MP furnace with a radiator inner diameter of 59 mm in 2019 [20, 21]. Based on the large area WC–C HTFP, NIM put forwarded a method for spectral irradiance measurement of the FEL lamp in the wavelength from 450 nm to 1000 nm [20]. Subsequently, in order to improve the measurement uncertainty of spectral irradiance measurement, NIM proposed a selective multiple fit method suitable to calculate the point of infection (POI) of large area HTFP [21], and then adopted Akima fitting method to recover the missing part of the melting plateau curve during spectral irradiance measurement [22]. In 2020, based on the large area HTFP, NIM completed the spectral irradiance scale realization in ultraviolet wavelength from 250 nm to 400 nm and in near infrared wavelength from 1100 nm to 2500 nm. Correlated colour temperature and distribution temperature of a tungsten filament lamp was realized also by this method. In addition, the measurement uncertainty of spectral irradiance based on large area HTFP was evaluated comprehensively. The new scale was compared with the values based on the variable temperature blackbody (HTBB) and the consistency was verified.

2. Spectral irradiance measurement facility based on a 14 mm WC–C fixed point blackbody

The regular (previous) spectral irradiance measurement facility of NIM is based on a variable-temperature blackbody [23] and measurements of its radiation temperature by a photoelectric pyrometer LP4, calibrated against three fixed point (Pt–C, Re–C and WC–C), traceably to the NIM realization of the Kelvin [14, 24, 25]. The expanded uncertainty of LP4 calibration is 1.0 K at the level of 3020 K. The new spectral irradiance facility based on WC–C fixed-point blackbody includes two WC–C fixed-point blackbodies, a large-cell blackbody with a 14 mm cavity diameter cell and a small-cell one with a 3 mm diameter cell. The pyrometer LP4 is used in this facility as a comparator and a monitor. The fixed-point method does not need a precise-calibrated pyrometer for absolute radiance temperature measurement; only relative temperature measurement is needed. Other elements are the same for both, previous and new, facilities: a series of quartz tungsten
halogen lamps, alignment lasers, input optics, a double-grating monochromator and a signal acquisition system. The diagram and photograph of the measurement facility, based on the WC–C fixed-point, are shown in figures 2 and 3, respectively.

A 14 mm cavity-diameter WC–C fixed point cell was installed inside the BB3500MP blackbody, so the originally variable-temperature blackbody turned into a large-area WC–C fixed-point blackbody. The new spectral irradiance scale was realized in the wavelength range from 250 nm to 2500 nm using the 14 mm diameter WC–C fixed-point blackbody.

The detail information of the blackbody, pyrometer, monochromator, detector, aperture, digital voltmeter, standard resistance, PTFE-coating integrating sphere, quartz tungsten halogen lamp used in the facility are listed in table 1.

In the process of spectral irradiance scale realization, the pyrometer LP4 registered the beginning and the end of the WC–C melting plateau. For the centre part, the HTFP blackbody was adjusted towards the spectral comparator for spectral irradiance measurement. The center wavelength of LP4 is 650 nm, and the diameter of target size is about 1 mm.

The input optics consists of a PTFE-coating integrating sphere, a spherical concave mirror with a diameter of 110 mm and a focal length of 550 mm and two flat mirrors. The image of the integrating sphere exit port is focused on the entrance slit of the monochromator with the magnification of 1. The integrating sphere was pressed from tetrafluoroethylene powder, and sintered at temperature higher than 300 °C.

The laser 1 is used to align the optical axis of double grating monochromator, flat mirror 2, concave mirror, flat mirror 1 and the exit port of integrating sphere. The lasers 2 and 3 are used to align the cavity of HTFP and the cross-hair centre of target of tungsten halogen lamp, respectively.

The spectral comparator of NIM is based on a double-grating monochromator M207D with a set of second order cut-on filters mounted in front of the entrance slit. Three pairs of gratings (1800, 1200 and 600 g mm\(^{-1}\)) are used to cover the whole wavelength range. A pen shaped low pressure mercury lamp is used for the monochromator wavelength calibration. The long-wavelength pass filters before the entrance slit of monochromator was removed, and the secondary and tertiary spectra of low-pressure mercury lamp are used to calibrate the spectral comparator in near-infrared band. The wavelength error was 0.04 nm, 0.03 nm and 0.09 nm in UV, VIS and NIR wavelength range, respectively. Three detectors were used for the whole wavelengths: photomultiplier R3896 (250 nm to 400 nm), Si detector (380 nm to 1100 nm) and thermoelectrically cooled InGaAs detector with temperature of minus 85 °C (800 nm to 2500 nm). A 226 Hz chopper and two-phase lock-in amplifier were used in infrared wavelength.

A precision water-cooled aperture was placed in front of the BB3500MP blackbody. An extension rod type micrometer was used to measure the distance between the aperture and the entrance diaphragm of the integrating sphere.

The area of precision aperture and the distance measuring micrometer were calibrated with uncertainties of 0.003 \(\mu\)m\(^2\) \((k = 2)\) and 0.0029 \(\mu\)m \((k = 2)\), respectively, with traceability to the NIM latest realization of the metre. The electrical measurements using the digital voltmeter 34420A with uncertainty of 0.022% \((k = 2)\) and the 0.001 \(\Omega\) standard resistor with uncertainty of 2.2 × 10\(^{-10}\) \(\Omega\) \((k = 2)\) were traceable to the latest realization of the ampere and volt at NIM. Traceability chain for the new spectral irradiance scale based on the WC–C fixed point blackbody and the scale based on the variable-temperature blackbody are shown schematically in figures 4(b) and (a), respectively.

3. Spectral irradiance scale realization with WC–C fixed point method

The isothermal radiation from the bottom of the high temperature blackbody cavity passed through a precise water-cooled aperture in front of the blackbody, and then projected to the entrance port of an integrating sphere at a specified field angle. The exit port of the integrating sphere was imaged on the entrance slit of double grating monochromator at 1:1 magnification. The radiation passed through the monochromator and was detected by one of three detectors (depending on wavelength range), which gave a signal \(V_{\lambda,B}\) proportional to the spectral irradiance. Spectral irradiance of the blackbody \(E_{\lambda,B}\) can be calculated as,

\[
E_{\lambda,B} = \frac{A}{d^2} \cdot \varepsilon_{\text{eff}} \cdot \frac{c_1}{\pi n^2 \cdot \lambda^5} \cdot \frac{1}{e^{2h\nu/T} - 1} \tag{1}
\]

where \(\varepsilon_{\text{eff}}\) is the blackbody emissivity, \(A\) is the area of the precision aperture, \(d\) is the distance between the precision aperture and the entrance port of the integration sphere, \(\lambda\) is the wavelength in air, \(n\) is the air refractive index, \(T\) is the thermodynamic temperature of the 14 mm WC–C fixed-point blackbody, \(c_1 = 2\pi \cdot h \cdot c^2 = 3.741 \times 711 852\ldots \times 10^{-16}\) W m\(^{-2}\) is the first radiation constant, \(c_2 = hc/k = 1.438 776 877\ldots \times 10^7\) nm K is the second radiation constant.

The geometric factor is represented by \(g\),

\[
g = \frac{A}{d^2} \tag{2}
\]

Spectral responsivity \(R_{\lambda}\) of the spectral comparing system can be calculated as

\[
R_{\lambda} = \frac{V_{\lambda,B}}{E_{\lambda,B}} \tag{3}
\]

When the signals \(V_{\lambda,B}\) had been measured, the translation stage moved to the specified position of the FEL lamp, and the signals \(V_{\lambda,L}\) were measured. Spectral irradiance of the lamp \(E_{\lambda,L}\) can be calculated according to the signal lamp-to-blackbody ratio over the specified wavelength range according to equation (4)

\[
E_{\lambda,L} = \frac{V_{\lambda,L}}{R_{\lambda}} \cdot \frac{A}{d^2} \cdot \varepsilon_{\text{eff}} \cdot \frac{c_1}{\pi n^2 \cdot \lambda^5} \cdot \frac{1}{e^{2h\nu/T} - 1} \cdot \frac{V_{\lambda,B}}{V_{\lambda,A}} \tag{4}
\]

3.1. Large-area WC–C blackbody temperature measurement

The previous investigation showed that thermodynamic temperature of a large-cell fixed point blackbody is a bit lower
than temperature of a small-cell one [19]. We suppose this difference is due to larger temperature drop across the back cavity wall because of larger radiation loss for the large cell (the phenomenon known as ‘temperature drop effect’). Our assumption is supported by the experiment described in [19], showed that the difference approximately doubled with doubling the thickness of the cavity bottom, which confirms the temperature-drop effect but not emissivity effect.

Nevertheless, we admit that other reasons, such as so called ‘furnace effect’ [26], might contribute to the cells temperature difference. This should be the subject of more thorough research. Within this paper the difference is associated with the temperature drop effect, and, therefore, consider as the temperature difference blackbody, and, thus, the associated spectral irradiance differences will be defined by the Planck’s law strictly. Regardless of the reason, the fact remains—there is a difference of large-to small-cell blackbodies. Moreover, the difference most likely depends on a furnace, but not only a cell (a kind of furnace effect), namely, on geometry and temperature distribution of the furnace. Therefore, for the fixed-point method, the temperature of the used large-area HTFP blackbody (at the specific combination of specific cell and furnace) should be measured first. For that the large cell WC–C blackbody was compared with the small WC–C blackbody from the facility shown in figure 2. The blackbodies were compared by the LP4 pyrometer. Full melt-freeze cycles of the small and large WC–C cells are shown in figure 5. The melting and freezing plateau were realized by applying the furnaces step of $+15$ K above and $-15$ K below the melting point of WC–C.

The melting points of the WC–C blackbodies was determined as the POI of the melting plateau using the new ‘selective multiple fit method’ developed at NIM [21]. Using the second derivative of the melting curve, we obtained the

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**Figure 2.** Diagram of the facility of spectral irradiance realization based on WC–C fixed point blackbody.

**Figure 3.** Photograph of the facility of spectral irradiance realization based on WC–C fixed point blackbody.
Table 1. Detail information of devices used in the spectral irradiance realization facility based on WC–C fixed-point blackbody.

| No. | Device                        | Type                  | Manufacturer                  | Descriptions and uncertainty ($k = 2$)                                                                 |
|-----|-------------------------------|-----------------------|--------------------------------|---------------------------------------------------------------------------------------------------------|
| 1   | Blackbody                     | BB3500MP              | VNIIOFI, Russia                | Temperature range: 1300 K–3500 K, Cavity: depth of 439 mm, diameter of 59 mm, effective opening diameter: 30 mm, emissivity: 0.9995 ± 0.0005.          |
|     |                               |                       |                                | Temperature range: 1800 K–3500 K, Cavity: depth of 300 mm, diameter of 38 mm, effective emissivity: 0.9995 ± 0.0003.                     |
| 2   | Blackbody                     | BB3500M               | VNIIOFI, Russia                | Type of insulation: Hybrid, Tungsten powder purity: 5N, Filling method: Drop, Ingot mass: 147.7 g, Length: 60 mm, Cavity diameter: 14 mm, Opening diameter: 14 mm, cavity depth: 44 mm. |
| 3   | 14 mm WC–C fixed point cell   | WC-C20D14             | VNIIOFI, Russia                | Type of insulation: Hybrid, Tungsten powder purity: 5N, Filling method: Drop, Ingot mass: 53.0 g, Length: 44.5 mm, Cavity diameter: 5 mm, Opening diameter: 3 mm, cavity depth: 34.4 mm. |
| 4   | 3 mm WC–C fixed point cell    | WC-C14                | VNIIOFI, Russia                | Spectral range: 1100 K–3300 K, Ke Technology Focal length: 700 mm, Temperature resolution: 0.001 K (used for relative measurement only). |
| 5   | Pyrometer                     | LP4                   | KE Technology GmbH, Germany    | Temperature range: 1800 K–3500 K, Cavity: depth of 300 mm, diameter of 38 mm, effective opening diameter: 20 mm, emissivity: 0.9995 ± 0.0003. |
| 6   | Monochromator                 | M207D                 | Mcpherson, U.S.A.              | Type of insulation: Hybrid, Tungsten powder purity: 5N, Filling method: Drop, Ingot mass: 147.7 g, Length: 60 mm, Cavity diameter: 14 mm, Opening diameter: 14 mm, cavity depth: 44 mm. |
| 7   | PMT detector                  | R7446                 | Hamamatsu, Japan               | Spectral range: 200 nm–3000 nm, Focal length: 0.67 m, f/No.: 5.8.                                        |
| 8   | Si detector                   | C10439-03             | Hamamatsu, Japan               | Spectral range: 200 nm–3000 nm, Focal length: 0.67 m, f/No.: 5.8.                                        |
| 9   | InGaAs detector               | J23TE4-3CN-R03M-2.6   | Teledyne Judson Technologies   | Spectral range: 900 nm to 2500 nm, Thermoelectric cooling temperature – 85 °C.                               |
| 10  | Water-cooled aperture         | φ5 mm                 | NIM, China                      | Temperature range: 1800 K–3500 K, Cavity: depth of 300 mm, diameter of 38 mm, effective opening diameter: 20 mm, emissivity: 0.9995 ± 0.0003. |
| 11  | Digital voltmeter             | 34420A                | Agilent                        | Spectral range: 200 nm–3000 nm, Focal length: 0.67 m, f/No.: 5.8.                                        |
| 12  | Standard resistance           | BZ6                   | Shanghai Ammeter               | Spectral range: 200 nm–3000 nm, Focal length: 0.67 m, f/No.: 5.8.                                        |
| 13  | PTFE-coating integrating sphere | 50 mm               | Changchun institute of optics  | Diameter of entrance port: 12 mm, 50 mm, Width and height of exit port: 2 mm and 10 mm                          |
|     |                               |                       | and machinery, China           |                                                                         |
| 14  | Quartz tungsten halogen lamp   | BN-9101               | Gigahertz-Optik, Germany       | Diameter of entrance port: 12 mm, 50 mm, Width and height of exit port: 2 mm and 10 mm                          |

duration of the melting plateau. The typical duration the large-area WC–C blackbody plateau was about 15 minutes, which was long enough to calibrate the spectral comparator at several typical wavelengths.

The comparison of the large- and small-cell WC–C blackbodies was performed in different three days. The temperature differences measured were $-0.51$ K, $-0.50$ K and $-0.46$ K, respectively. The average difference was $-0.49$ K. The melting temperature of the large-cell WC–C fixed point blackbody was defined as 3020.11 K using the average value of the WC–C fixed point, 3020.60 K, based on available measured values for small cells [17, 18, 27, 28]. In future, after the RealK project [12], the value of the WC–C fixed point might be updated.

### 3.2. Measurement procedure

The procedure of the spectral irradiance scale realization based on 14 mm diameter WC–C HTFP was as follows. Firstly, the optical platform was moved to the position of the optical axis...
of the HTFP, and the radiance temperature of the HTFP was monitored by the pyrometer LP4. The first melt-freeze cycle of the large cell was recorded by the pyrometer, and the duration of the melting plateau was defined. When the second melting plateau appeared, the optical platform was moved quickly to the position of the spectral comparator to measure the signal of the HTFP at several wavelengths. When the measurement was completed, the optical platform was quickly moved back to the position of the pyrometer to monitor the end of the melting curve [20, 22]. Because of limited number of spectral points could be measured by a comparator during one melting plateau, a few melt/freezecycles were done to cover the whole spectral range from 250 nm to 2500 nm.

3.3. Fitting and correcting of melting plateau

During the measurement period, the melting plateau of the WC–C HTFP blackbody cannot be fully monitored, but only the beginning and the end of the plateau was recorded by the pyrometer as it is shown in figure 6, the solid line.

The Akima fitting method was used to restore the missing part of the melting plateau curve [22]. Figure 6 shows the fitting result: the measured data at the beginning and the end of the melting plateau, and the central recovered data by using the Akima fitting method. The accuracy of the Akima method for POI definition was approximately 0.005 K.

The above melting curve is a curve of the pyrometer readings (in Kelvin). The values of the pyrometer readings, in general case, differ from the actual temperature of the blackbody, for instance because of wrong calibration or drift of the pyrometer. Here we do not need a well calibrated pyrometer, which was used as a monitor only. Therefore in general case the value of the pyrometer temperature reading in the POI is different from 3020.11 K. Therefore, after restoring the melting plateau, which is based on the pyrometer reading records, we corrected it (by adding the same delta temperature value to the whole curve) in such a way that the temperature in the POI of the corrected plateau was equal to 3020.11 K—the fixed-point temperature of the large-cell WC–C blackbody.

3.4. Spectral irradiance scale realization

A precision aperture with the area of 20.479 mm$^2$ was placed in front of the blackbody, which was used to limit the field of view of the spectral comparator to receive only the uniform radiation from the bottom of the cell cavity. When calibration of the spectral comparator against the fixed-point blackbody was completed, the optical platform was moved to the position of the standard lamp to measure spectral irradiance. The distance between the lamp and the integrating sphere was 500 mm and the distance between the blackbody aperture and the integrating sphere was 611 mm.

The stable centre part duration of the melting plateau of the large-area WC–C blackbody was about 12 minutes, therefore the measurement time of spectral irradiance should be less than 12 minutes, which means that the number of spectral points measured at one melt should be limited. Our spectral irradiance measurement was divided into three spectral intervals: UV covered the wavelengths from 250 nm to 400 nm with step of 10 nm; visible covered the wavelengths from 390 nm to 1000 nm with step of 50 nm to 100 nm; and IR covered the wavelengths from 1100 nm to 2500 nm with step of 100 nm. Thus, three melts of WC–C fixed point were enough to measure the whole range from 250 nm to 2500 nm for one time. The measurements were repeated several times.

4. Uncertainty budget

Measurement uncertainties of spectral irradiance based on 14 mm WC–C fixed point blackbody from 250 nm to 2500 nm were evaluated at NIM, according to equation (4), which we rewrite here in the following form:

$$\frac{E_{\lambda, L}}{E_{\lambda, B}} = \frac{A}{\pi} \cdot K_g \cdot \varepsilon_{\text{eff}} \cdot \pi \cdot n^2 \cdot L^3 \left( e^{\frac{c_i}{\lambda N_A}} + 3T_u + 3T_a \right) - 1 \times \frac{V_{\lambda, L}}{V_{\lambda, B}} \cdot K_{\text{current}} \cdot K_{l, \lambda} + \delta E_{\lambda, L}$$

Where, $K_g$ is the approximation of geometric factor $g$, $\delta T_u$ is the non-uniformity of the temperature of blackbody cavity, $\delta T_a$ is the Akima approximation error of the melting plateau curve of the fixed-point blackbody, $K_{\text{current}}$ is the impact factor of lamp current on spectral irradiance, $K_{l, \lambda}$ is the non-linearity factor of measurement system, $\delta E_{\lambda, L}$ is stray light of the system.
Figure 5. Typical melt-freeze cycles of small (left) and large (right) WC–C cell.

Figure 6. Recovering melting plateau (solid line—the measured data; dot line—recovered data using the Akima fitting method).

The uncertainty budget includes the following sources: repeatability, reproducibility of realignment, temperature measurement of HTFP, non-uniformity of HTFP, Akima approximation of HTFP, emissivity, area of water-cooled aperture, current, non-linearity of measurement system, wavelength accuracy, spectral bandwidth, distance, approximation of geometric factor $g$, air refractive index $n$, stray light etc. The uncertainty components are presented in Table 2.

4.1. Repeatability

More than six repeated measurements were carried out separately. The repeatability uncertainties were calculated as the relative standard deviation of the measured signal ratios $V_{\lambda, L}/V_{\lambda, B}$.

4.2. Reproducibility of realignment

More than three independent measurements were carried out after re-installation and re-alignment of the fixed-point blackbody, tungsten halogen lamps and measurement system. Then the reproducibility uncertainties were calculated as relative standard deviations of spectral irradiance for tungsten halogen lamps.

4.3. Temperature measurement of HTFP

For WC–C small-cell blackbody, the average value of the published measured thermodynamic temperatures (POI) is 3020.6 K ($u = 0.35$ K, $k = 1$) [18]. However, the temperature of cell may vary from cell to cell. The typical non-reproducibility of small WC–C cells is 0.035 K [29]. We added this value as the standard uncertainty component associated with non-reproducibility of the small WC–C cell we used.

As it was shown in [18], the long-term instability of the WC–C cell (small cell of the same design and the same producer than the cell we used) might be estimated as 0.12 K per 140 melts. The cell used in this investigation was rather new and went through approximately 20 melts. Therefore, the long-term instability of this cell can be estimated as 0.017 K. The uncertainty associated with long-term instability of the small WC–C cell was estimated as 0.010 K assuming a rectangle probability distribution.

The difference between the large- and small-cell WC–C blackbodies was measured at NIM to be minus 0.49 K with standard uncertainty of 0.06 K, which included the following components: reproducibility of measurements (0.03 K), repeatability of the large cell (0.01 K), repeatability of the small cell (0.01 K), stability of LP4 (0.03 K) and the size of source effect of LP4 (0.04 K).

The combined standard uncertainty of the melting temperature at POI (3020.11 K) for the 14 mm large-area WC–C HTFP blackbody was 0.36 K.

The relative uncertainty of spectral irradiance contributed by temperature measurement of the fixed-point blackbody was calculated according to the equation

$$u = u_{T}\frac{c_2}{(n\lambda T^2)}$$

The uncertainties of spectral irradiance are shown in Table 2.

4.4. Non-uniformity of HTFP

Non-uniformity of the fixed-point blackbody was measured by means of scanning the effective aperture area, by the pyrometer.
Table 2. Uncertainty budget of spectral irradiance scale based on the WC–C fixed-point blackbody.

| Source of uncertainty | 250  | 280  | 300  | 350  | 380  | 400  | 600  | 800  | 1000 | 1100 | 1500 | 2000 | 2300 | 2500 |
|-----------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 100 × Type A uncertainty | Repeatability | Uncorrelated | 1.500 | 0.500 | 0.200 | 0.100 | 0.100 | 0.050 | 0.030 | 0.030 | 0.030 | 0.200 | 0.200 | 0.300 |
|                       | Reproducibility of realignment | Correlated | 1.200 | 0.400 | 0.150 | 0.100 | 0.100 | 0.040 | 0.030 | 0.030 | 0.030 | 0.150 | 0.200 | 0.200 |
|                       | Temperature | Correlated | 0.227 | 0.203 | 0.189 | 0.162 | 0.149 | 0.142 | 0.095 | 0.071 | 0.057 | 0.052 | 0.038 | 0.028 |
|                       | Measurement of HTFP | Correlated | 0.058 | 0.052 | 0.049 | 0.042 | 0.038 | 0.036 | 0.024 | 0.018 | 0.015 | 0.013 | 0.010 | 0.007 |
|                       | Non-uniformity of HTFP | Correlated | 0.006 | 0.006 | 0.005 | 0.005 | 0.004 | 0.003 | 0.002 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 |
|                       | Akima approximation of HTFP | Correlated | 0.020 | 0.020 | 0.020 | 0.020 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
|                       | Emissivity | Correlated | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 |
|                       | Area of water-cooled aperture | Correlated | 0.140 | 0.130 | 0.120 | 0.100 | 0.090 | 0.080 | 0.050 | 0.030 | 0.020 | 0.020 | 0.010 | 0.010 |
|                       | Current | Correlated | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.090 | 0.080 | 0.080 | 0.100 | 0.100 | 0.100 | 0.100 |
|                       | Non-linearity of measurement system | Correlated | 0.020 | 0.020 | 0.020 | 0.020 | 0.020 | 0.020 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
|                       | Wavelength | Correlated | 0.046 | 0.028 | 0.022 | 0.008 | 0.049 | 0.004 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
|                       | Bandwidth | Correlated | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 |
|                       | Distance | Correlated | 0.034 | 0.030 | 0.028 | 0.023 | 0.021 | 0.020 | 0.120 | 0.008 | 0.006 | 0.005 | 0.002 | 0.001 |
|                       | Air refractive index n Approximation of geometric factor g | Correlated | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 |
|                       | Stray light | Correlated | 0.05  | 0.03  | 0.03  | 0.03  | 0.03  | 0.03  | 0.03  | 0.03  | 0.03  | 0.03  | 0.03  | 0.03  |
| 100 × combined uncertainty of uncorrelated | | | 1.50 | 0.50 | 0.20 | 0.10 | 0.10 | 0.05 | 0.03 | 0.03 | 0.03 | 0.20 | 0.20 | 0.30 |
| 100 × combined uncertainty of correlated | | | 1.24 | 0.49 | 0.30 | 0.25 | 0.24 | 0.21 | 0.16 | 0.13 | 0.12 | 0.20 | 0.23 | 0.32 |
| 100 × combined uncertainty $u_c (k = 1)$ | | | 1.95 | 0.70 | 0.36 | 0.27 | 0.26 | 0.21 | 0.16 | 0.13 | 0.12 | 0.28 | 0.31 | 0.38 |
| 100 × U (k = 2) | | | 3.89 | 1.39 | 0.72 | 0.54 | 0.52 | 0.43 | 0.32 | 0.27 | 0.25 | 0.56 | 0.62 | 0.76 | 0.88 | 2.42 |
LP4 and was found to be 0.16 K at 3020.11 K. The uncertainty associated with non-uniformity was estimated as 0.0924 K assuming a rectangle probability distribution.

The relative uncertainty of spectral irradiance was calculated according to the equation (6).

4.5. Akima approximation of HTFP melting curve

The maximum deviation of the Akima fitting approximation from the measured melting curve was 0.017 K according to our experiment. Therefore, the uncertainty associated with the Akima method is 0.01 K assuming a rectangle probability distribution. The corresponding relative uncertainty of spectral irradiance were calculated according to the equation (6).

4.6. Emissivity of the WC–C fixed point blackbody

Emissivity $\varepsilon_{eff}$ of the 14 mm WC–C fixed point blackbody and its uncertainty was estimated based on the Monte Carlo modelling using the STEEP3 software [30]. The emissivity was estimated to be 0.9997 with the standard uncertainty varied from 0.0001 to 0.0002 [19].

4.7. Area of water-cooled aperture

The area of precise water-cooled aperture was 20.479 mm$^2$, and the relative measurement uncertainty is 0.003 mm$^2$. The relative uncertainty of spectral irradiance contributed by area of water-cooled aperture was 0.0146%, which was traceable to the latest realization of Length at NIM.

4.8. Current of the tungsten halogen lamps

The spectral irradiance of tungsten halogen lamp is strongly dependent on the electrical parameters assigned to it. Therefore, it is important to set and keep the lamp current at its defined value. The lamp current was monitored during the measurements and turned out to change less than 1 mA for lamps during measurements. The associated spectral irradiance uncertainties were evaluated and listed in table 2.

4.9. Non-linearity of measurement system

Three detectors were used for the whole wavelength, and double aperture method was used to measure the non-linearity of the measuring system between 0.1 mV and 120 mV. In the wavelength range from 250 nm to 400 nm, a PMT detector was used. The signal ratio of tungsten halogen lamp and HTFP was varied from 3.2 to 4.3, and the non-linearity was less than 0.10%. From 450 nm to 1000 nm, a Si detector was used. The signal ratio was varied from 3.7 to 4.3, and the non-linearity was varied from 0.09% to 0.08%. From 1100 nm to 2500 nm, an InGaAs detector was used. The signal ratio was varied from 2.8 to 3.4, and the non-linearity was less than 0.10%.

4.10. Wavelength accuracy

The maximum wavelength errors of the spectral comparator were 0.04 nm, 0.03 nm and 0.09 nm in UV, visible and IR wavelength range, respectively. Spectral irradiance of tungsten halogen lamp was calculated from the lamp-to-blackbody signal ratio; therefore, the uncertainties contributed by wavelength accuracy can be calculated as the relative deviations of $E_{lamp}(\lambda \pm \Delta \lambda)/E_{BB}(\lambda \pm \Delta \lambda)$ and $E_{lamp}/E_{BB}$.

4.11. Spectral bandwidth

The uncertainty due to spectral bandwidth is calculated and shown in table 2.

4.12. Distance

The distance was measured by an extension rod type micrometer (Chengdu instrument factory), which was calibrated by the division of dimensional metrology at NIM with uncertainty of 0.0053 mm. The positions of the precise aperture, the lamp front plate and the integrating sphere entrance port were aligned by laser and preserved by three plumb lines. The distance between two plumb lines was measured by the micrometer at least 6 times, and the maximum divergence of six measurements was lower than 0.02 mm. The maximum tilt and rotation adjustment uncertainty of the sphere entrance port were estimated to be 0.05 mm. Therefore, the combined standard uncertainty of distance measurement was 0.074 mm.

Distances between the aperture and the sphere was 611 mm, and between the lamp and the sphere was 500 mm; thus, the relative uncertainties of spectral irradiance contributed by distances were 0.024% and 0.030% for the lamp and blackbody, respectively. The total relative uncertainty of spectral irradiance contributed by distance was 0.038%.

4.13. Air refractive index $n$

Estimation of $n$ depends on a model and air conditions such as temperature, pressure, humidity. Air refractive index $n$ varies from 1.0003014 at 250 nm to 1.0002728 at 2500 nm. Varying these parameters, the standard uncertainty of $n$ was estimated as 0.00002. The blackbody spectral irradiance uncertainty associated with $n$ varied from 0.034% at 250 nm to 0.000% at 2500 nm, which is calculated by using the Planck law.

4.14. Approximation of geometric factor $g$

In the derivation of geometric factor $g$ in equation (2), it is assumed that the distance $d$ is far greater than the diameter of entrance port of integrating sphere and the diameter of water-cooled aperture. For our facility, the accurate calculated value of $g$ is $5.4844 \times 10^{-5}$, and the approximate value is $5.48563 \times 10^{-5}$, so the uncertainty of approximation of geometric factor $g$ is about 0.022%.

4.15. Stray light

Generally, stray light consists of dark count, external stray light and internal stray light.

Dark count was measured by closing the shutter and was subtracted from measured signal in our experiment.

External stray light may reach the detector from outside the main field of view, which was evaluated by blocking the direct...
beam from the lamp using a small screen and detecting the signal with and without this beam block. Uncertainty associated with external stray light was estimated to be lower than 0.02% for all wavelengths [31].

Internal stray light comes from light that scatters within the spectral comparator and therefore reaches a pixel for the ‘wrong’ wavelength. In our experiment, a stable tungsten halogen lamp and two 380 nm cut-off filters were used to evaluate the internal stray light of double grating monochromator M207D. The signal with the filters was compared to the signal without the filters for the shorter wavelengths. According to the spectral transmittance of the 380 nm cut-on filters, internal stray light was calculated as 0.03% at 250 nm. The total stray light was estimated to be 0.05% at 250 nm, 0.04% at 260 nm and 0.03% at other wavelengths.

The overall uncertainty budget of spectral irradiance scale of tungsten halogen lamps based on the 14 mm diameter WC–C fixed-point blackbody realized at NIM is shown in table 2 and figure 7.

The expanded uncertainties of the new spectral irradiance scale are 3.9% at 250 nm, 1.4% at 280 nm, 0.43% at 400 nm, 0.27% at 800 nm, 0.25% at 1000 nm, 0.62% at 1500 nm, 0.76% at 2000 nm, and 2.4% at 2500 nm, respectively.

5. Comparison of the spectral irradiance scale based on the fixed-point blackbody with that based on the variable temperature blackbody

The spectral irradiance scale realized on the basis of the 14 mm WC–C fixed-point blackbody was compared with the scale based on a variable temperature blackbody (HTBB) BB3500M. A 1000 W quartz tungsten halogen FEL lamp, type BN-9101, was used as the transfer standard from 250 nm to 2500 nm. The lamp was calibrated against both blackbodies alternately: the 14 mm WC–C HTFP and the HTBB. Figure 8 shows the relative deviation between the two calibrations.

The divergence of the two methods varied from −0.66% to 0.79% from 280 nm to 2100 nm, and the maximum deviation is 1.13% at 2500 nm, which were consistent to the associated measurement uncertainties. The measurement uncertainty of the two methods is shown in figures 9 and 10.

In the range from 300 nm to 1000 nm use of the fixed-point blackbody improves the scale obviously (figure 10): the uncertainties are decreased by more than 25% compared to the scale based on the variable temperature blackbody [32]. The most significant reason is that the measurement uncertainty of temperature was reduced from 0.64 K to 0.36 K. The long-term instability of the large area HTFP may not be
considered because the temperature was measured just before the experiment by comparing with the small-cell blackbody. In addition, the temperature uniformity of HTFP was also slightly improved. Below 270 nm the fixed-point blackbody method shows higher uncertainty due to relatively low signal-to-noise ratio. In the wavelength range above 1100 nm, the influence of temperature measurement accuracy decreases, therefore, the uncertainty of two methods are almost at the same level.

6. Realization of correlated colour temperature and distribution temperature based on fixed-point blackbody

Relative spectral distribution of a tungsten filament lamp in the 380 nm to 780 nm measured by using the 14 mm WC–C HTFP was used to calculate the correlated colour temperature and distribution temperature, which were compared with the values based on the HTBB measurements. The maximum relative deviation of spectral distribution based on the two methods was less than 1.0%.

Correlated colour temperature and distribution temperature realized based on the two methods are listed in Table 3. The deviation of colour temperature based on two methods is $-0.50 \text{ K}$, and the distribution temperature is $-2.9 \text{ K}$.

7. Conclusions

Spectral irradiance in the wavelength from 250 nm to 2500 nm, correlated colour temperature and distribution temperature scales based on a 14 mm diameter WC–C HTFP was realized at NIM. The consistency of spectral irradiance between the HTFP method and the HTBB method was better than 0.8% from 280 nm to 2100 nm. However, the measurement results at 250 nm and near-infrared band are not ideal owing to the lower signal-to-noise ratio. The next step is to improve the signal level by using a photon counting detector (UV), a high sensitive NIR detector and a combination of absolute and relative measurement method [16].

When the spectral irradiance of an FEL lamp is directly calibrated by using a large area WC–C HTFP, the uncertainty of the lamp will be reduced significantly from 300 nm to 1000 nm compared to the HTBB method. This lamp can be used as a transfer standard alone or together with a diffuser to calibrate the lower level standard lamps, integrating sphere sources, and spectroradiometers with low uncertainty. In this way, the measurement uncertainties of the end users will also be reduced.

The large-area WC–C fixed-point blackbody has been tried to calibrate the spectroradiometers directly in the field of remote sensing at NIM. This method can shorten the traceability chain and improve the calibrating accuracy of spectral irradiance responsivity and spectral radiance responsivity. In addition, a large area 2856 K δMoC–C fixed-point cell is intended for realizing correlated colour temperature, distribution temperature and photometric scale, which has more similar spectral distribution with the tungsten filament lamp.

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Conflict of interest

The authors declare no conflicts of interest.

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