Bilateral comparison of local realizations of the ITS-90 between the silver point and 1700 °C using vacuum tungsten strip lamps as transfer standards between the NRC and the PTB

**Final Report**

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## Introduction

At its 19th session in September 1996, the Consultative Committee for Thermometry (CCT) agreed to conduct an international key comparison of the local realisations of the International Temperature Scale (ITS) of 1990 above the silver point. High-stability tungsten-strip lamps were selected to be used as transfer standards. The measurements began in 1997 and ended in July 1999. The comparison was piloted by the NMi-VSL and co-piloted by the NPL. The national metrology institutes of 12 countries participated in this key comparison and the initial Draft A report was circulated in October 1999. With the circulation of the report, some participants became aware of problems with their local scale realisations. After identifying and correcting the root causes of the discrepancies, the NRC asked PTB to pilot a bilateral comparison to link their improved local scale realisation to the CCT-K5 results. The measurements were carried out from June 2001 to October 2002. This report presents the results of the NRC-PTB bilateral comparison.

## Organisation

Two high-stability vacuum tungsten-strip lamps, C598 and 644C, served as transfer standards for this bilateral comparison. The comparison was piloted by the Physikalisch-Technische Bundesanstalt of Germany (PTB) and the lamps were supplied by the National Research Council of Canada (NRC). The measurements were performed according to the protocol for the CCT-K5 key comparison. Due to the good lamp stability following transport observed during CCT-K5, the initialization tests were omitted.

The measurements at the PTB and the NRC were corrected to the reference conditions stated in the CCT-K5 protocol. In detail, the reference conditions define:

(a) the orientation of the strip
(b) a base temperature of 20 °C
(c) a wavelength of 650 nm
(d) a set of eleven defined current settings (related to each lamp)

## Results

The standard radiation thermometers used for the comparison are described in detail in the reports of the participants (Annexes A and B of this report). In brief, the NRC realised its high temperature scale using a calibrated radiation thermometer. This radiation thermometer directly measures the temperature of the lamps used in this comparison. A copper fixed-point blackbody radiator was used as the primary reference source. At the PTB, the standard IR radiation thermometer was used to transfer the temperature of the primary gold fixed point to two lamps, which were operated at 1337 K and 1800 K. These lamps were used to calibrate a third lamp at different temperatures. This third lamp was used to calibrate the comparison lamps using the standard IR radiation thermometer.

Tables 1 and 2 summarize the main features of the respective radiation thermometers and fixed-point radiators used to realise the high-temperature scales of the PTB and the NRC.

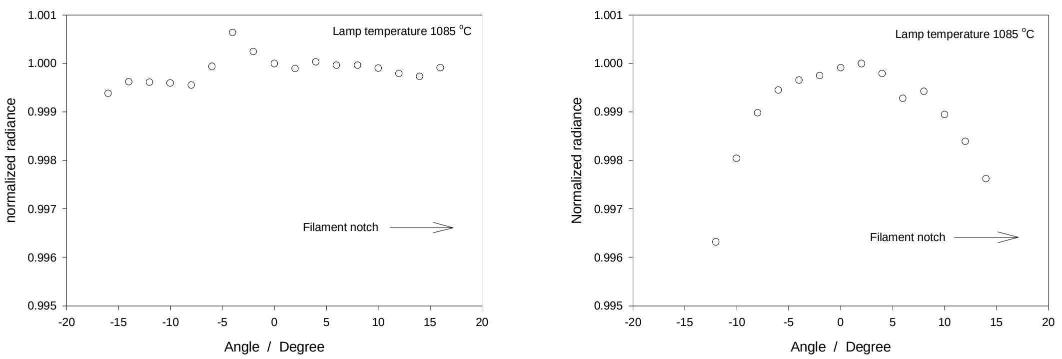
**Table 1:** Summary of the major parameters of the radiation thermometers used for the bilateral comparison

| Laboratory | Target Distance [mm] | Target size [mm] | f-number | Central wavelength [nm] | FWHM [nm] | Optics |
|---|---|---|---|---|---|---|
| NRC | 500 | 0.6 | 7.7 and 24 | 650 | 10 | Lenses |
| PTB | 1220 | 0.5 | 15 | 653 | 18 | Mirrors |

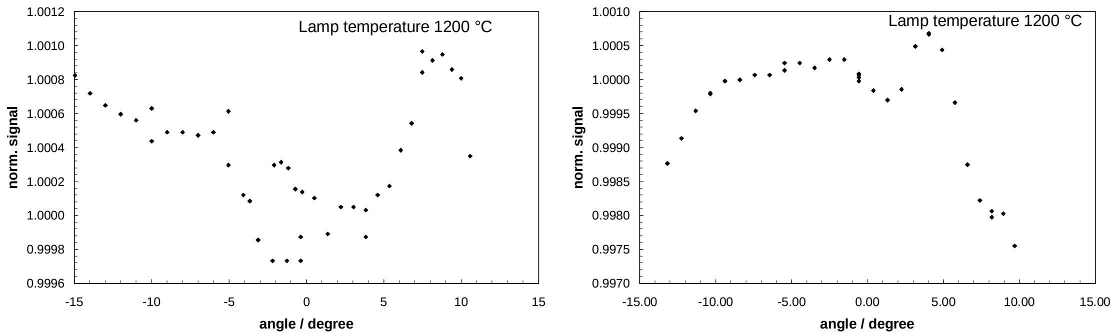
**Table 2:** Summary of the parameters of the fixed points used for the bilateral comparison and the calculation method.

| Laboratory | Fixed point material | Fixed point purity [%] | Fixed point emissivity | Calculation method |
|---|---|---|---|---|
| NRC | Cu | 99.999 | 0.99997 | effective wavelength |
| PTB | Au | 99.999 | 0.99999 | effective wavelength |

The initial study of the angular dependence (Fig. 1) and the horizontal variation (Fig. 2) of the emitted spectral radiance showed no interreflections in the measured positions and sufficiently flat temperature profiles, indicating good measurement conditions for both participating laboratories.




a)




b)

Figure 1: Measured angular dependence of the spectral radiance of lamp C598 (left) and 644C (right): a) at the NRC, b) at the PTB.

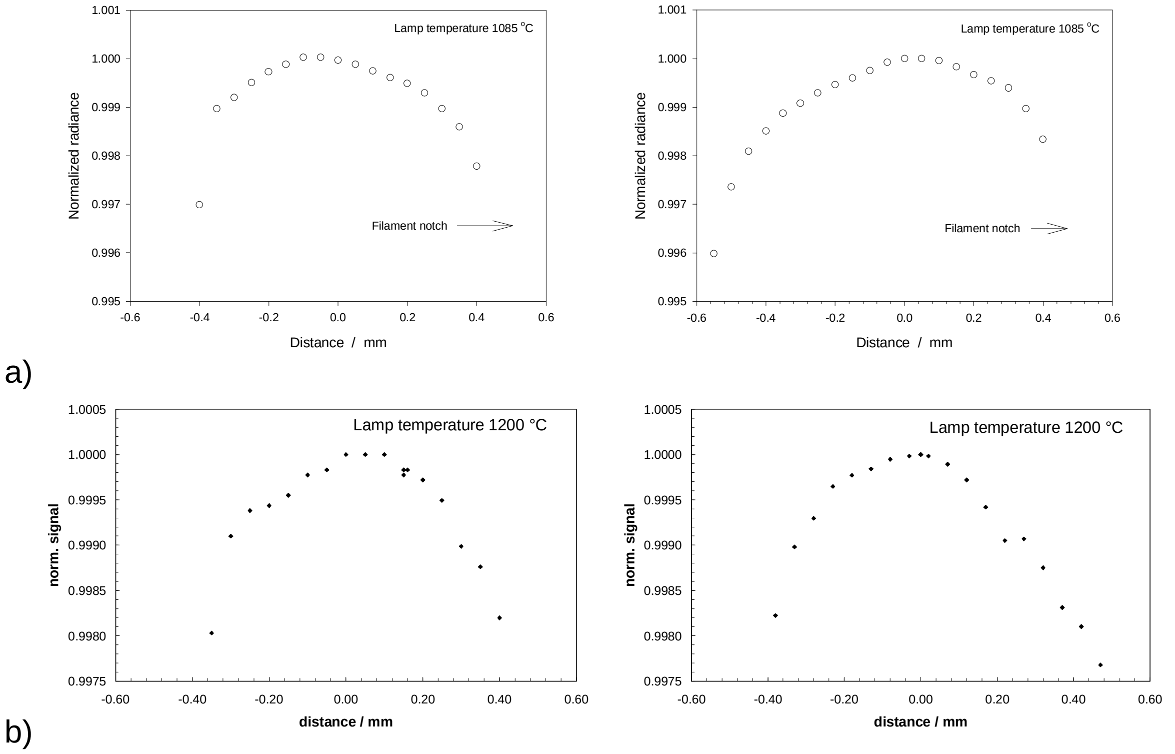



Figure 2: Measured horizontal distribution of the spectral radiance of lamp C598 (left) and 644C (right): a) at the NRC, b) at the PTB.

Both laboratories measured each lamp at least twice at each temperature value. At the NRC the lamps were measured on two occasions, before they were transfered to the PTB and after their return, and the results of these two measurement series have been averaged. Figures 3 and 4 show the deviation of the radiance temperatures between the PTB and the NRC. The results and the respective uncertainties are given in Tables 3 to 8.

**Table 3:** The radiance temperatures of lamp C598 as measured at the PTB.

| I(C598) [A] | Ts650(C598) [°C] | u (*k*=1) [°C] |
|---|---|---|
| 5.027 | 962.12 | 0.15 |
| 5.298 | 999.86 | 0.16 |
| 5.808 | 1064.48 | 0.17 |
| 5.981 | 1084.81 | 0.17 |
| 6.116 | 1100.32 | 0.18 |
| 7.054 | 1200.14 | 0.19 |
| 8.092 | 1300.06 | 0.21 |
| 9.210 | 1400.21 | 0.24 |
| 10.393 | 1500.17 | 0.26 |
| 11.635 | 1600.51 | 0.29 |
| 12.930 | 1700.43 | 0.32 |

**Table 4:** The radiance temperatures of lamp 644C as measured at the PTB.

| I(644C) [A] | Ts650(644C) [°C] | u (*k*=1) [°C] |
|---|---|---|
| 5.184 | 962.16 | 0.15 |
| 5.457 | 999.97 | 0.16 |
| 5.966 | 1064.46 | 0.17 |
| 6.141 | 1085.09 | 0.17 |
| 6.277 | 1100.35 | 0.18 |
| 7.223 | 1200.28 | 0.19 |
| 8.276 | 1300.27 | 0.21 |
| 9.411 | 1400.27 | 0.24 |
| 10.617 | 1500.46 | 0.26 |
| 11.880 | 1600.55 | 0.29 |
| 13.197 | 1700.63 | 0.32 |

**Table 5a:** The radiance temperatures of lamp C598 as measured at the NRC prior to the measurements at the PTB

| I(C598) [A] | Ts650(C598, NRC_I) [°C] | u (*k*=1) [°C]* |
|---|---|---|
| 5.027 | 962.28 | 0.19 |
| 5.298 | 1000.02 | 0.20 |
| 5.808 | 1064.51 | 0.22 |
| 5.981 | 1084.92 | 0.23 |
| 6.116 | 1100.40 | 0.24 |
| 7.054 | 1200.26 | 0.27 |
| 8.092 | 1300.32 | 0.33 |
| 9.210 | 1400.46 | 0.38 |
| 10.393 | 1500.75 | 0.40 |
| 11.635 | 1600.90 | 0.45 |
| 12.930 | 1700.97 | 0.50 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

**Table 5b:** The radiance temperatures of lamp C598 as measured at the NRC following the measurements at the PTB

| I(C598) [A] | Ts650(C598, NRC_II) [°C] | u (*k*=1) [°C]* |
|---|---|---|
| 5.027 | 962.16 | 0.19 |
| 5.298 | 999.89 | 0.20 |
| 5.808 | 1064.39 | 0.22 |
| 5.981 | 1084.78 | 0.23 |
| 6.116 | 1100.28 | 0.24 |
| 7.054 | 1200.13 | 0.27 |
| 8.092 | 1300.08 | 0.33 |
| 9.210 | 1400.16 | 0.38 |
| 10.393 | 1500.24 | 0.40 |
| 11.635 | 1600.33 | 0.45 |
| 12.930 | 1700.35 | 0.50 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

**Table 5c:** Average result for the radiance temperatures of lamp C598 as measured at the NRC.

| I(C598) [A] | Ts650(C598, NRC_average) [°C] | u (*k*=1) [°C]* |
|---|---|---|
| 5.027 | 962.22 | 0.19 |
| 5.298 | 999.95 | 0.20 |
| 5.808 | 1064.45 | 0.22 |
| 5.981 | 1084.85 | 0.23 |
| 6.116 | 1100.34 | 0.24 |
| 7.054 | 1200.19 | 0.27 |
| 8.092 | 1300.20 | 0.33 |
| 9.210 | 1400.31 | 0.38 |
| 10.393 | 1500.50 | 0.40 |
| 11.635 | 1600.61 | 0.45 |
| 12.930 | 1700.66 | 0.50 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

**Table 6a:** The radiance temperatures of lamp 644C measured at the NRC prior to the measurements at the PTB

| I(644C) [A] | Ts650(644C, NRC_I) [°C] | u (*k*=1) [°C]* |
|---|---|---|
| 5.185 | 962.30 | 0.19 |
| 5.457 | 1000.21 | 0.20 |
| 5.966 | 1064.51 | 0.22 |
| 6.141 | 1085.04 | 0.23 |
| 6.276 | 1100.47 | 0.24 |
| 7.223 | 1200.38 | 0.27 |
| 8.276 | 1300.44 | 0.33 |
| 9.411 | 1400.45 | 0.38 |
| 10.617 | 1500.78 | 0.40 |
| 11.880 | 1600.84 | 0.45 |
| 13.197 | 1700.94 | 0.50 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

**Table 6b:** The radiance temperatures of lamp 644C as measured at the NRC following the measurements at the PTB

| I(644C) [A] | Ts650(644C, NRC_II) [°C] | u (*k*=1) [°C]* |
|---|---|---|
| 5.185 | 962.14 | 0.19 |
| 5.457 | 1000.07 | 0.20 |
| 5.966 | 1064.40 | 0.22 |
| 6.141 | 1084.93 | 0.23 |
| 6.276 | 1100.34 | 0.24 |
| 7.223 | 1200.29 | 0.27 |
| 8.276 | 1300.23 | 0.33 |
| 9.411 | 1400.18 | 0.38 |
| 10.617 | 1500.41 | 0.40 |
| 11.880 | 1600.54 | 0.45 |
| 13.197 | 1700.50 | 0.50 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

**Table 6 c:** Average result for the radiance temperatures of lamp 644C as measured at the NRC.

| I(644C) [A] | Ts650(644C, NRC_average) [°C] | u (*k*=1) [°C]* |
|---|---|---|
| 5.185 | 962.22 | 0.19 |
| 5.457 | 1000.14 | 0.20 |
| 5.966 | 1064.46 | 0.22 |
| 6.141 | 1084.98 | 0.23 |
| 6.276 | 1100.40 | 0.24 |
| 7.223 | 1200.33 | 0.27 |
| 8.276 | 1300.34 | 0.33 |
| 9.411 | 1400.31 | 0.38 |
| 10.617 | 1500.59 | 0.40 |
| 11.880 | 1600.69 | 0.45 |
| 13.197 | 1700.72 | 0.50 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

**Table 7:** Differences between the radiance temperatures of lamp C598 measured at the NRC and the PTB

| I(C598) [A] | dT(NRC_I-PTB) [°C] | dT(NRC_II-PTB) [°C] | dT(NRC_average-PTB) [°C] | $u_{combined}$ (*k*=1) [°C] |
|---|---|---|---|---|
| 5.027 | 0.16 | 0.04 | 0.10 | 0.24 |
| 5.298 | 0.15 | 0.02 | 0.09 | 0.26 |
| 5.808 | 0.03 | -0.09 | -0.03 | 0.28 |
| 5.981 | 0.11 | -0.04 | 0.03 | 0.29 |
| 6.116 | 0.08 | -0.04 | 0.02 | 0.30 |
| 7.054 | 0.12 | -0.02 | 0.05 | 0.33 |
| 8.092 | 0.27 | 0.02 | 0.15 | 0.39 |
| 9.210 | 0.25 | -0.05 | 0.10 | 0.45 |
| 10.393 | 0.58 | 0.07 | 0.33 | 0.48 |
| 11.635 | 0.39 | -0.18 | 0.10 | 0.53 |
| 12.930 | 0.54 | -0.08 | 0.23 | 0.60 |

**Table 8:** Differences between the radiance temperatures of lamp 644C measured at the NRC and the PTB

| I(644C) [A] | dT(NRC_I-PTB) [°C] | dT(NRC_II-PTB) [°C] | dT(NRC_average-PTB) [°C] | $u_{combined}$ (*k*=1) [°C] |
|---|---|---|---|---|
| 5.185 | 0.14 | -0.02 | 0.06 | 0.24 |
| 5.457 | 0.24 | 0.11 | 0.18 | 0.26 |
| 5.966 | 0.05 | -0.06 | 0.00 | 0.28 |
| 6.141 | -0.05 | -0.15 | -0.10 | 0.29 |
| 6.276 | 0.11 | -0.01 | 0.05 | 0.30 |
| 7.223 | 0.10 | 0.01 | 0.06 | 0.33 |
| 8.276 | 0.17 | -0.05 | 0.06 | 0.39 |
| 9.411 | 0.18 | -0.09 | 0.04 | 0.45 |
| 10.617 | 0.32 | -0.05 | 0.14 | 0.48 |
| 11.880 | 0.29 | -0.02 | 0.14 | 0.53 |
| 13.197 | 0.31 | -0.13 | 0.09 | 0.60 |

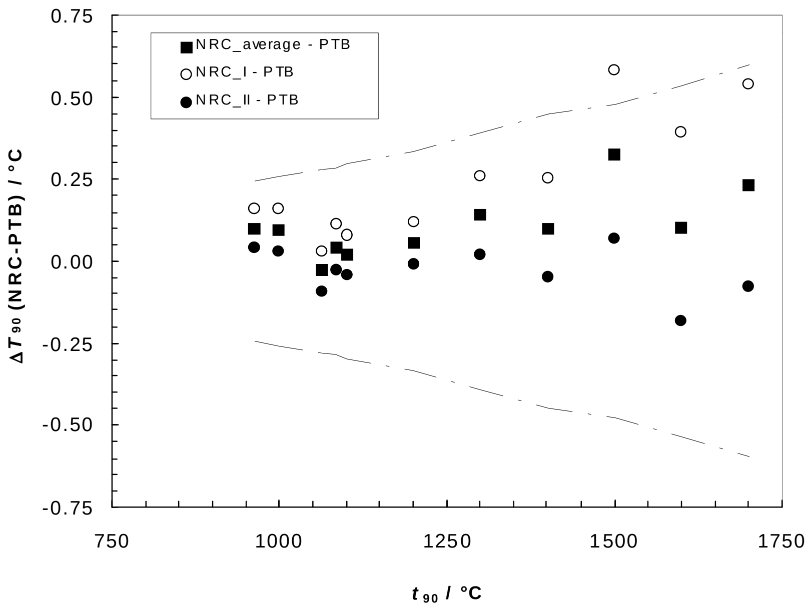



**Figure 3:** Differences in the radiance temperatures of lamp C598 as measured at the NRC and the PTB. (NRC_I, NRC_II, NRC_average: temperature measured at the NRC for the first and second run, and average temperature measured at the NRC, respectively. Dotted line: combined standard uncertainty at *k*=1)

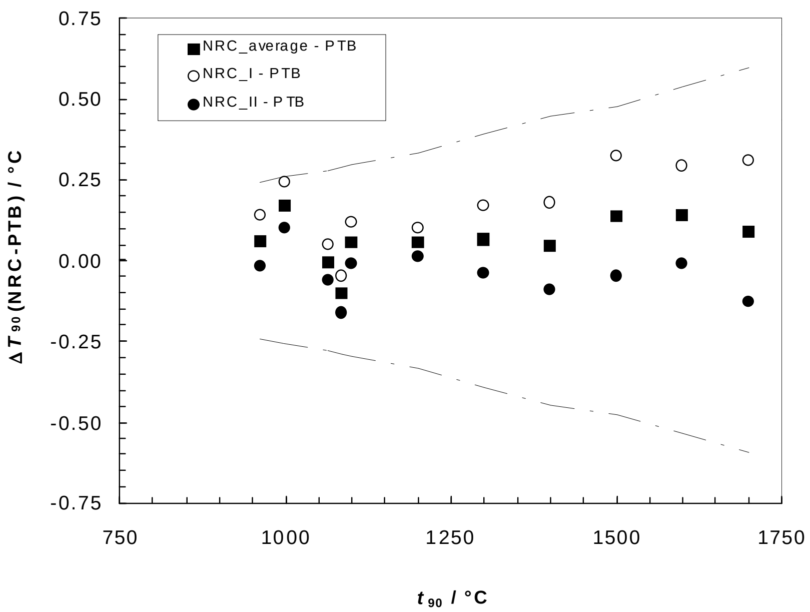



**Figure 4:** Differences in the radiance temperatures of lamp 644C as measured at the NRC and the PTB. (NRC_I, NRC_II, NRC_average: temperature measured at the NRC for the first and second run, and average temperature measured at the NRC, respectively. Dotted line: combined standard uncertainty at *k*=1)

## Annex A: Report of the PTB

**January 2004**

# Report on the calibration of the tungsten strip lamps C598 and 644C within the bilateral CCT key-comparison “Local realizations of the ITS-90 between the Silver point and 1700 °C using vacuum Tungsten-strip lamps as transfer standards” between the NRC and the PTB

By J. Hartmann

## I. Experimental and theoretical procedure

**The realisation of the ITS- 90, the description of the equipment and the experimental procedure are described in the following references:**

1. J. Fischer, H.J. Jung, R. Friedrich, “A new determination of the freezing temperature of gold relative to that of silver by radiation thermometry“, Temperature **6**, 53-57 (1992);
2. J. Fischer, H.J. Jung, "Determination of the thermodynamic temperatures of the freezing points of silver and gold by near-infrared pyrometry", Metrologia **26**, 245-252 (1989);

The formal definition and derivation of the spectral radiance temperature with explicit reference to the corrections applied together with the transfer of the radiance temperature to the strip lamp is described in

3. J. Fischer, J. Hartmann, “Calibration of tungsten strip lamps as transfer standards for temperature” Proceedings of Tempmeko´99;
4. H.-J. Jung, J. Verch; “Ein Rechenverfahren zur Auswertung pyrometrischer Messungen“, Optik **38**, 95-109 (1973)

In this report, only a short description of the reference thermometer characteristics is given.

The limiting effective wavelength $\lambda_e$ is calculated for every lamp at every current according to Refs. 3 and 4 and is given in the final Tables 5 to 6 in the column $\lambda_e$. The measured beam is limited to a diameter of 20 mm. The reference pyrometer has a focal length of 300 mm yielding an *f*-number of 20/300=1/15. The target distance is 1220 mm and the target field is circular, with a diameter of 0.5 mm.

The size-of source-effect (SSE) with respect to a gold fixed-point blackbody with an aperture of 3 mm diameter (effective source diameter 30 mm) was measured for the two wavelengths (650 nm and 950 nm) for two different strip widths. The results are given in Table 1.

| Wavelength / nm | SSE for the 1.5 mm strip | SSE for the 3 mm strip |
|---|---|---|
| 650 | $6.89 \times 10^{-4}$ | $5.26 \times 10^{-4}$ |
| 950 | $7.13 \times 10^{-4}$ | $4.24 \times 10^{-4}$ |

**Table 1:** Size-of-source effect measured with respect to a gold fixed point with an aperture of 3 mm diameter (effective source diameter 30 mm) for two strip widths.

The transfer lamps C598 and 644C

The transfer lamps delivered to PTB on June 19th, 2001 during the TEMPMEKO 2001 conference, and transferred to NRC on May 18th, 2002, during the NEWRAD 2002 conference. The conditions of the measurements together with the total burning times for both lamps are given in Table 2.

| | Lamp P598 | Lamp 644C |
|---|---|---|
| Orientation | as prescribed in the protocol | as prescribed in the protocol |
| Base temperature $T_B$ | 20 °C ± 0.1 °C | 20 °C ± 0.1 °C |
| Total burning time | 57 h | 57 h |
| Ambient temperature (aver.) | 23 °C | 23 °C |

**Table 2:** Measurement conditions for the two lamps C598 and 644C.

The measured horizontal and angular distributions of the strip radiance temperatures are presented in Fig. 1-2.

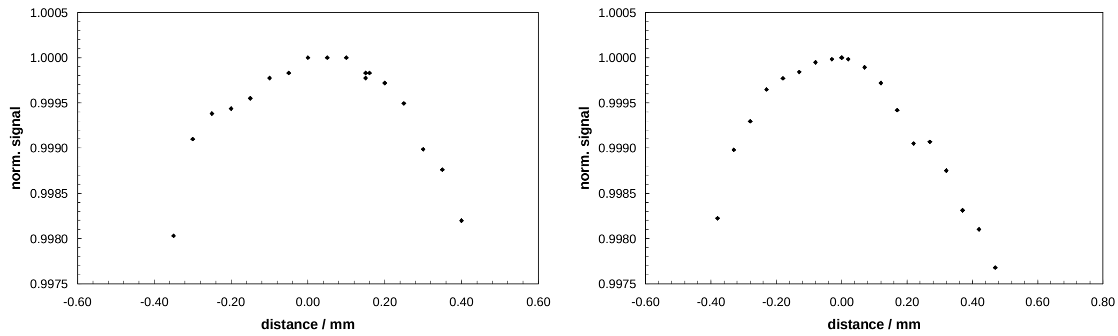



**Figure 1:** Horizontal distribution of the signal along the strip obtained for lamps C598 (left) and 644C (right). The signals were normalized to the signal at the middle of the strip. The signals were recorded at a nominal radiance temperature of 1200 °C.

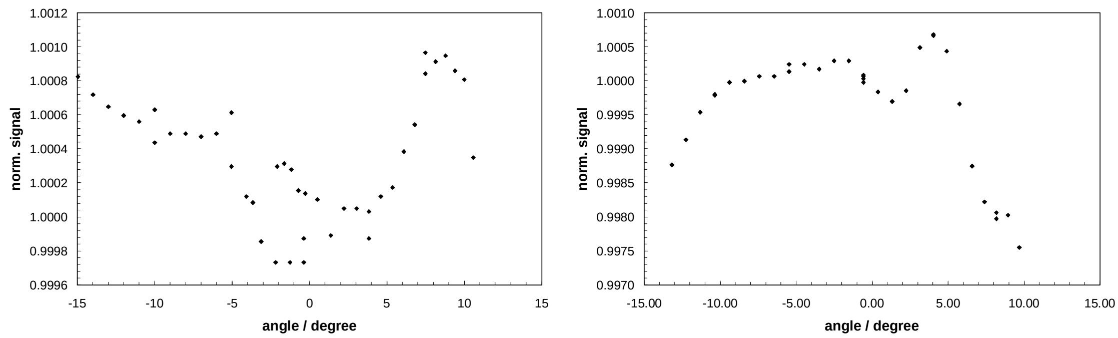



**Figure 2:** Angular distribution of the signal when rotating the lamps (C598 on the left, 644C on the right) on an axis perpendicular to the optical axis and to the floor. The signals were normalized with respect to the signal at zero angle. The signals were recorded at a nominal radiance temperature of 1200 °C.

## II. Uncertainties-Identification of uncertainty components

The calibration scheme consisted of three steps (see Ref. 3): First, two first-order working standards (WS) were calibrated with reference to the primary standard gold fixed-point blackbody. These two first-order WS (C514 and C520) were operated at only one radiance temperature (C514 at 1800 K, C520 at 1337 K).

In a second step, a second-order WS (P95) was calibrated with reference to the two first order WS at different radiance temperatures. In the last step, the lamps C598 and 644C were calibrated with reference to the second order WS at nearly the same radiance temperatures.

In the following, the contributions to the overall uncertainty are given separately for each calibration step. The uncertainties $u_i$ are given at a coverage factor $k$=1.

a) Calibration of the first order WS with reference to the gold fixed point blackbody

1. Realization of the reference temperature of the gold fixed point. This uncertainty is caused by the impurity of the gold ingot (5N, i.e. 0.99999), the emissivity of the cavity (0.99996±0.00001) and the temperature difference $\Delta T$ across the bottom of the cavity (<1 mK). The realisation of the reference temperature $T_r$=1337.33 K is within ±0.01 K resulting in a standard uncertainty for the radiance temperature of

$$u_2 = \frac{0.01\text{K}}{\sqrt{3}}\left(\frac{T}{T_r}\right)^2$$

2. Long term stability of the interference filters used (includes the mean effective wavelength, the spectral transmission of the interference filter, the spectral responsivity of the detector): ±0.05 nm resulting in a standard uncertainty for the radiance temperature of

$$u_3 = T\left(\frac{T}{T_r} - 1\right)\frac{0.05\text{ nm}}{\lambda\sqrt{3}}$$

3. Uncertainty in radiance comparison including a lamp (spatial and angular distribution of the spectral radiance, cleaning of the window, alignment, ratio of feedback resistors, non-linearity, SSE)

$\Delta L/L$=1.5x$10^{-3}$.

This results in a standard uncertainty of radiance temperature of (with $c_2$ being Planck's second radiation constant)

$$u_4 = \frac{1.5\cdot 10^{-3}}{\sqrt{3}}\frac{\lambda T^2}{c_2}$$

4. Uncertainty due to the measurement of the lamp current. With a relative uncertainty $u$=2.4x$10^{-5}$ for the voltage measurement and $u$=1x$10^{-5}$ for the standard resistor we obtain a resulting standard uncertainty in radiance temperature (with d$T$/d$i$ being the slope of the lamp characteristic $T$=$T$($i$))

$$u_5 = i\left(\frac{dT}{di}\right)\cdot\sqrt{\left(10^{-5}\right)^2 + \left(2.4\cdot 10^{-5}\right)^2}$$

5. Short term stability of a vacuum tungsten strip lamp of 0.1 K resulting in a standard uncertainty of radiance temperature

$$u_9 = \frac{0.1\text{K}}{\sqrt{3}}$$

b) Calibration of lamp P95 with reference to Lamps C514 and C520

1. When comparing two sources with different radiance temperatures, an uncertainty arises due to poor blocking of the interference filter caused by parasitic transmission at long wavelengths. Using “edge filters” (RG780, RG715 and RG9), a rough estimate of the standard uncertainty in radiance temperature can be made, which is presented in Table 3.

| ***T* / K** | $u_1$ / K | $T$ / K | $u_1$ / K |
|---|---|---|---|
| 900 | 0,16 | 1500 | 0,01 |
| 1100 | 0,03 | 1700 | 0,02 |
| 1300 | 0,00 | 1900 | 0,02 |

**Table 3:** Standard uncertainty in radiance temperature due to blocking error with reference to a blackbody at 1337 K.

2. Realisation of the reference temperature

$$u_2 = u_2(\text{first order WS})(T/T_r)^2$$

3. Long term stability of the interference filter $u_3$
4. Uncertainty in radiance comparison including a lamp $u_4$
5. Measurement of the lamp current $u_5$
6. Influence of the temperature of the base. The standard deviation for maximum changes of the base temperature $T_b$ of ±0.1 K is (with $\mathrm{d}T_S/\mathrm{d}T_B$ being the change in radiance temperature when changing the base temperature by 1 K)

$$u_6 = \frac{dT_S}{dT_B}\frac{0.1\text{K}}{\sqrt{3}}$$

6. Resolution of the IR-pyrometer in terms of the photocurrents equals $\pm 2\text{x}10^{-15}$ A. The photocurrent at 650 nm and 1337 K is $5{,}4\text{x}10^{-10}$ A. The standard deviation for resolution in radiance temperature is then

for 650 nm $$u_7 = \frac{2\cdot 10^{-15}}{5.4\cdot 10^{-10}}\cdot\frac{\exp\left(\dfrac{c_2}{650\,\text{nm}\cdot 1337.33\,K}\right)}{\exp\left(\dfrac{c_2}{650\,\text{nm}\cdot T}\right)}\cdot\frac{\left(650\,\text{nm}\dfrac{T^2}{c_2}\right)}{\sqrt{3}}$$

7. Short term stability of the vacuum tungsten strip lamps $u_9$

c) Calibration of lamps C598 and 644C with reference to Lamp P95

1. Realisation of the reference temperature
   $u_2=u_2(\text{second order WS})(T/T_r)^2$
2. Long term stability of the interference filter $u_3$
3. Uncertainty in radiance comparison including a lamp: in contrast to the first two calibration steps an uncertainty in radiance of $\Delta L/L=2.0\text{x}10^{-3}$ is considered for $u_4$ as the lamps C598 and 644C have not been investigated as thoroughly as the lamps C514, C520 and P95
4. Measurement of the lamp current $u_5$
5. Influence of the temperature of the base $u_6$

6. Resolution of the IR-pyrometer in terms of the photocurrents $u_7$
7. Short term stability of the vacuum tungsten strip lamps $u_9$

Summarizing all of the uncertainties mentioned above, the final overall uncertainty at the coverage factor $k$=1 presented in Table 4 is obtained.

Table 4 a)

| T (650 nm)/K | Uncertainty (k=1, 650 nm) / K |
|---|---|
| | |
| 1235.15 | 0.15 |
| 1273.15 | 0.16 |
| 1337.15 | 0.17 |
| 1358.15 | 0.17 |
| 1373.15 | 0.18 |
| 1473.15 | 0.19 |
| 1573.15 | 0.21 |
| 1673.15 | 0.24 |
| 1773.15 | 0.26 |
| 1873.15 | 0.29 |
| 1973.15 | 0.32 |

Table 4 b)

| T (950 nm)/K | Uncertainty (k=1, 950 nm) / K |
|---|---|
| | |
| 1192.63 | 0.19 |
| 1227.82 | 0.19 |
| 1286.82 | 0.21 |
| 1306.18 | 0.22 |
| 1320.09 | 0.22 |
| 1411.67 | 0.24 |
| 1502.63 | 0.27 |
| 1592.85 | 0.30 |
| 1682.42 | 0.34 |
| 1771.34 | 0.37 |
| 1859.75 | 0.41 |

Table 4: Overall uncertainty as a function of radiance temperature for 650 nm wavelength ( a) and for 950 nm wavelength ( b)

## III Calibration results

The calibration results for lamp C598 are shown in Tables 5 a) to d) for the 650 nm wavelength. The calibration results for lamp 644C are shown in Tables 6 a) to d) for the 650 nm wavelength.

The tables are slightly modified compared to the tables prescribed in the protocol as we left out some corrections. First, no corrections have been made for non-linearity and water absorption. These two effects were considered within the uncertainty budget. Second, no corrections due to the base temperature were made, as our temperature stabilization is sufficiently accurate and stable. A possible effect due to a slight variation has been considered in the uncertainty budget. Third, the control of the strip current is accurate and stable, so no correction for this has been applied (see columns 2-4). However, as we performed a Spline interpolation to the measured radiance temperatures to identify measurement errors (see Ref. 3), we applied an additional correction shown in the column named “Spline correction “in Tables 5 to 6.

First measurement on lamp C598 at 650 nm

Table 5 a)

| No | I(j) / A | I(l) / A | I(j)-I(l) / A | R=i(C598)/i(F | Ts(P95 at 650F | Tλ / K | Tλ / K corrected fo | Tλ / K corrected for SSE and non-linearity |
|---|---|---|---|---|---|---|---|---|
| 1 | 4.933 | 5.027 | -0.094 | 0.80599999 | 1250 | 1234.857 | 1234.866 | 1234.866 |
| 2 | 5.236 | 5.298 | -0.062 | 1.36575694 | 1250 | 1272.554 | 1272.564 | 1272.564 |
| 3 | 5.788 | 5.808 | -0.02 | 0.85483756 | 1350 | 1337.123 | 1337.134 | 1337.134 |
| 4 | 5.980 | 5.981 | -0.001 | 1.09358924 | 1350 | 1357.457 | 1357.468 | 1357.468 |
| 5 | 6.120 | 6.116 | 0.00405 | 1.31188381 | 1350 | 1372.884 | 1372.895 | 1372.895 |
| 6 | 7.107 | 7.054 | 0.0530333 | 1.26251577 | 1450 | 1472.637 | 1472.651 | 1472.651 |
| 7 | 8.177 | 8.092 | 0.085 | 1.22471791 | 1550 | 1572.468 | 1572.483 | 1572.483 |
| 8 | 9.314 | 9.210 | 0.104 | 1.19627421 | 1650 | 1672.488 | 1672.505 | 1672.505 |
| 9 | 10.513 | 10.393 | 0.12 | 1.17227203 | 1750 | 1772.416 | 1772.435 | 1772.435 |
| 10 | 11.767 | 11.635 | 0.1319 | 1.60504858 | 1800 | 1872.509 | 1872.530 | 1872.530 |
| 11 | 13.074 | 12.930 | 0.144 | 2.90904851 | 1800 | 1972.362 | 1972.386 | 1972.386 |

Table 5 b)

| No | λe / nm | Tλ / K | dTλ/dλ / (K/ | dTλ/dλ(λr-λe | Tλ(λr=650nm) / | Tλ(λr=650nm) | Spline correction / | Tλ(λr=650nm; I(j) ) / °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 654.284 | 1234.866 | -0.111 | 0.474 | 1235.340 | 962.190 | -0.006 | 962.184 |
| 2 | 654.256 | 1272.564 | -0.118 | 0.500 | 1273.064 | 999.914 | -0.004 | 999.910 |
| 3 | 654.210 | 1337.134 | -0.130 | 0.548 | 1337.682 | 1064.532 | 0.054 | 1064.586 |
| 4 | 654.197 | 1357.468 | -0.134 | 0.564 | 1358.032 | 1084.882 | 0.000 | 1084.882 |
| 5 | 654.187 | 1372.895 | -0.138 | 0.576 | 1373.471 | 1100.321 | -0.048 | 1100.273 |
| 6 | 654.128 | 1472.651 | -0.160 | 0.660 | 1473.310 | 1200.160 | -0.006 | 1200.154 |
| 7 | 654.076 | 1572.483 | -0.184 | 0.752 | 1573.235 | 1300.085 | 0.017 | 1300.102 |
| 8 | 654.030 | 1672.505 | -0.211 | 0.851 | 1673.357 | 1400.207 | 0.007 | 1400.214 |
| 9 | 653.989 | 1772.435 | -0.240 | 0.958 | 1773.394 | 1500.244 | -0.043 | 1500.201 |
| 10 | 653.953 | 1872.530 | -0.271 | 1.072 | 1873.603 | 1600.453 | 0.046 | 1600.499 |
| 11 | 653.920 | 1972.386 | -0.304 | 1.193 | 1973.579 | 1700.429 | -0.018 | 1700.411 |

Second measurement on lamp C598 at 650 nm

Table 5 c)

| No | I(j) / A | I(l) / A | I(j)-I(l) / A | R=i(C864)/i(F | Ts(P95 at 650F | Tλ / K | Tλ / K corrected fo | Tλ / K corrected for SSE and non-linearity |
|---|---|---|---|---|---|---|---|---|
| 1 | 4.933 | 5.027 | 0.0002 | 0.80454539 | 1250 | 1234.732 | 1234.741 | 1234.741 |
| 2 | 5.236 | 5.298 | 0 | 0.65974395 | 1300 | 1272.451 | 1272.456 | 1272.456 |
| 3 | 5.788 | 5.808 | 0 | 0.92146967 | 1350 | 1336.973 | 1336.978 | 1336.978 |
| 4 | 5.98 | 5.981 | -0.0002 | 1.17955975 | 1350 | 1357.354 | 1357.360 | 1357.360 |
| 5 | 6.12 | 6.116 | -1E-04 | 1.31214692 | 1400 | 1372.901 | 1372.912 | 1372.912 |
| 6 | 7.107 | 7.054 | 0.0051 | 1.26219391 | 1500 | 1472.612 | 1472.625 | 1472.625 |
| 7 | 8.177 | 8.092 | -1E-04 | 1.22404396 | 1600 | 1572.406 | 1572.421 | 1572.421 |
| 8 | 9.314 | 9.210 | 1E-04 | 1.19588499 | 1700 | 1672.447 | 1672.464 | 1672.464 |
| 9 | 10.513 | 10.393 | -1E-04 | 0.97876073 | 1800 | 1772.382 | 1772.391 | 1772.391 |
| 10 | 11.767 | 11.635 | -1E-04 | 1.61830319 | 1800 | 1872.542 | 1872.553 | 1872.553 |
| 11 | 13.074 | 12.930 | -1E-04 | 2.92543766 | 1800 | 1972.412 | 1972.428 | 1972.428 |

Table 5 d)

| No | λe / nm | Tλ / K | dTλ/dλ / (K/ | dTλ/dλ(λr-λe | Tλ(λr=650nm) / | Tλ(λr=650nm) | Spline correction / | Tλ(λr=650nm; I(j) ) / °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 654.284 | 1234.741 | -0.111 | 0.474 | 1235.215 | 962.065 | -0.003 | 962.061 |
| 2 | 654.256 | 1272.456 | -0.118 | 0.500 | 1272.956 | 999.806 | 0.007 | 999.813 |
| 3 | 654.210 | 1336.978 | -0.130 | 0.548 | 1337.526 | 1064.376 | -0.005 | 1064.372 |
| 4 | 654.197 | 1357.360 | -0.134 | 0.564 | 1357.924 | 1084.774 | -0.030 | 1084.743 |
| 5 | 654.187 | 1372.912 | -0.138 | 0.576 | 1373.488 | 1100.338 | 0.037 | 1100.375 |
| 6 | 654.128 | 1472.625 | -0.160 | 0.660 | 1473.285 | 1200.135 | -0.006 | 1200.129 |
| 7 | 654.076 | 1572.421 | -0.184 | 0.752 | 1573.173 | 1300.023 | -0.012 | 1300.011 |
| 8 | 654.030 | 1672.464 | -0.211 | 0.851 | 1673.315 | 1400.165 | 0.040 | 1400.206 |
| 9 | 653.989 | 1772.391 | -0.240 | 0.958 | 1773.349 | 1500.199 | -0.059 | 1500.140 |
| 10 | 653.953 | 1872.553 | -0.271 | 1.072 | 1873.626 | 1600.476 | 0.047 | 1600.523 |
| 11 | 653.920 | 1972.428 | -0.304 | 1.193 | 1973.622 | 1700.472 | -0.016 | 1700.456 |

Table 5: Results of the calibration of the lamp C598 at 650 nm for the first measurement ( a), b) ) and for the second measurement ( c), d) )

First measurement on lamp 644C at 650 nm

Table 6 a)

| No | I(j) / A | I(l) / A | I(j)-I(l) / A | R=i(644C)/i(F | Ts(P95 at 650F | Tλ / K | Tλ / K corrected for | Tλ / K corrected for SSE and non-linearity |
|---|---|---|---|---|---|---|---|---|
| 1 | 5.185 | 5.185 | 1E-04 | 0.80574006 | 1250 | 1234.834 | 1234.844 | 1234.844 |
| 2 | 5.457 | 5.457 | 1E-04 | 1.36801877 | 1300 | 1272.676 | 1272.686 | 1272.686 |
| 3 | 5.966 | 5.966 | 1E-04 | 0.85422178 | 1350 | 1337.064 | 1337.075 | 1337.075 |
| 4 | 6.141 | 6.142 | -0.00145 | 1.09771344 | 1350 | 1357.773 | 1357.784 | 1357.784 |
| 5 | 6.276 | 6.276 | 0 | 1.31289983 | 1400 | 1372.950 | 1372.962 | 1372.962 |
| 6 | 7.223 | 7.223 | 0 | 1.26413085 | 1500 | 1472.763 | 1472.777 | 1472.777 |
| 7 | 8.276 | 8.276 | 0 | 1.22674868 | 1600 | 1572.654 | 1572.669 | 1572.669 |
| 8 | 9.411 | 9.411 | -1E-04 | 1.19660599 | 1700 | 1672.523 | 1672.541 | 1672.541 |
| 9 | 10.617 | 10.617 | 0 | 1.17363189 | 1800 | 1772.582 | 1772.601 | 1772.601 |
| 10 | 11.880 | 11.880 | 0 | 1.60536235 | 1800 | 1872.540 | 1872.562 | 1872.562 |
| 11 | 13.197 | 13.197 | 0 | 2.91125544 | 1800 | 1972.496 | 1972.520 | 1972.520 |

Table 6 b)

| No | λe / nm | Tλ / K | dTλ/dλ / (K/ | dTλ/dλ(λr-λe | Tλ(λr=650nm) / | Tλ(λr=650nm) | Spline correction / | Tλ(λr=650nm; I(j) ) / °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 654.284 | 1234.844 | -0.111 | 0.474 | 1235.318 | 962.168 | 0.031 | 962.199 |
| 2 | 654.256 | 1272.686 | -0.118 | 0.500 | 1273.186 | 1000.036 | -0.062 | 999.974 |
| 3 | 654.210 | 1337.075 | -0.130 | 0.548 | 1337.623 | 1064.473 | 0.036 | 1064.509 |
| 4 | 654.197 | 1357.784 | -0.134 | 0.564 | 1358.348 | 1085.198 | 0.027 | 1085.226 |
| 5 | 654.187 | 1372.962 | -0.138 | 0.576 | 1373.538 | 1100.388 | -0.026 | 1100.362 |
| 6 | 654.127 | 1472.777 | -0.160 | 0.660 | 1473.437 | 1200.287 | -0.012 | 1200.274 |
| 7 | 654.076 | 1572.669 | -0.184 | 0.752 | 1573.421 | 1300.271 | 0.004 | 1300.276 |
| 8 | 654.030 | 1672.541 | -0.211 | 0.851 | 1673.392 | 1400.242 | 0.012 | 1400.254 |
| 9 | 653.989 | 1772.601 | -0.240 | 0.958 | 1773.559 | 1500.409 | -0.025 | 1500.385 |
| 10 | 653.953 | 1872.562 | -0.271 | 1.072 | 1873.634 | 1600.484 | 0.021 | 1600.505 |
| 11 | 653.920 | 1972.520 | -0.304 | 1.193 | 1973.713 | 1700.563 | -0.007 | 1700.556 |

Second measurement on lamp 644C at 650 nm

Table 6 c)

| No | I(j) / A | I(l) / A | I(j)-I(l) / A | R=i(644C)/i(F | Ts(P95 at 650F | Tλ / K | Tλ / K corrected for | Tλ / K corrected for SSE and non-linearity |
|---|---|---|---|---|---|---|---|---|
| 1 | 5.185 | 5.184 | 0.0002 | 0.80481937 | 1250 | 1234.755 | 1234.765 | 1234.765 |
| 2 | 5.457 | 5.457 | 0 | 0.79913236 | 1300 | 1272.649 | 1272.656 | 1272.656 |
| 3 | 5.966 | 5.966 | 0 | 0.92154794 | 1350 | 1336.978 | 1336.983 | 1336.983 |
| 4 | 6.141 | 6.141 | -0.0002 | 1.18174774 | 1350 | 1357.508 | 1357.514 | 1357.514 |
| 5 | 6.276 | 6.277 | -1E-04 | 1.31266917 | 1400 | 1372.935 | 1372.946 | 1372.946 |
| 6 | 7.223 | 7.223 | 0.0051 | 1.26397554 | 1500 | 1472.751 | 1472.764 | 1472.764 |
| 7 | 8.276 | 8.276 | -1E-04 | 1.22684656 | 1600 | 1572.663 | 1572.678 | 1572.678 |
| 8 | 9.411 | 9.411 | 1E-04 | 1.19690962 | 1700 | 1672.556 | 1672.573 | 1672.573 |
| 9 | 10.617 | 10.617 | -1E-04 | 1.03797444 | 1800 | 1772.708 | 1772.721 | 1772.721 |
| 10 | 11.880 | 11.880 | -1E-04 | 1.61519335 | 1800 | 1872.663 | 1872.677 | 1872.677 |
| 11 | 13.197 | 13.197 | -1E-04 | 2.92923899 | 1800 | 1972.642 | 1972.658 | 1972.658 |

Table 6 d)

| No | λe / nm | Tλ / K | dTλ/dλ / (K/ | dTλ/dλ(λr-λe | Tλ(λr=650nm) / | Tλ(λr=650nm) | Spline correction / | Tλ(λr=650nm; I(j) ) / °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 654.284 | 1234.765 | -0.111 | 0.474 | 1235.238 | 962.088 | 0.025 | 962.113 |
| 2 | 654.256 | 1272.656 | -0.118 | 0.500 | 1273.156 | 1000.006 | -0.049 | 999.957 |
| 3 | 654.210 | 1336.983 | -0.130 | 0.548 | 1337.531 | 1064.381 | 0.030 | 1064.411 |
| 4 | 654.197 | 1357.514 | -0.134 | 0.564 | 1358.078 | 1084.928 | 0.019 | 1084.947 |
| 5 | 654.187 | 1372.946 | -0.138 | 0.576 | 1373.523 | 1100.373 | -0.025 | 1100.347 |
| 6 | 654.127 | 1472.764 | -0.160 | 0.660 | 1473.425 | 1200.275 | 0.004 | 1200.278 |
| 7 | 654.076 | 1572.678 | -0.184 | 0.752 | 1573.430 | 1300.280 | -0.009 | 1300.271 |
| 8 | 654.030 | 1672.573 | -0.211 | 0.851 | 1673.424 | 1400.274 | 0.009 | 1400.283 |
| 9 | 653.989 | 1772.721 | -0.240 | 0.959 | 1773.679 | 1500.529 | -0.003 | 1500.526 |
| 10 | 653.953 | 1872.677 | -0.271 | 1.073 | 1873.750 | 1600.600 | -0.002 | 1600.598 |
| 11 | 653.920 | 1972.658 | -0.304 | 1.194 | 1973.851 | 1700.701 | 0.001 | 1700.703 |

Table 6: Results of the calibration of the lamp 644C at 650 nm for the first measurement ( a), b) ) and for the second measurement ( c), d) )

## Annex B: Report of the NRC

# Report on the realization of the ITS-90 between the silver freezing point and 1700 °C at the National Research Council of Canada for the bilateral comparison between PTB and NRC

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The format of this report follows closely that of [1]. Section titles and numbers that are in Times New Roman font with the italic style are taken from the same reference. Notations in this report closely follow those in the reference and deviations from it are minor and self-explanatory. The terminology (as expressed in the use of the terms ‘effective wavelength’ and ‘blackbody radiator’) closely follows the reference.

*4. Reporting*

*4.1. Experimental and theoretical procedures*

*4.1.1. Realization of the ITS-90*

- *Description of equipment, including reference thermometer and reference fixed-point blackbody radiator.*

Our pyrometer comprises an interference filter, a photoelectric detector, aperture stops, converging lenses, and ancillaries (Fig. 4.1.1). The matched objective achromatic lenses of 69 mm diameter and 500 mm focal length project an image (1:1) of the target area onto a circular field stop of 0.6 mm diameter. The center wavelength of the interference filter is 650 nm and the full width at half maximum transmittance is 10 nm. The homemade detector assembly comprises a silicon photodiode (Hamamatsu S1226-5BQ), an operational amplifier, and a feedback resistor (1 GΩ).

Two Cu fixed-point blackbodies were used as reference radiators. The first was used for the measurements before the lamps were sent to PTB. It was broken near the end of the measurement. The second was used for the measurements following the return of the lamps.

- *Description of experimental procedures*

The calibration of the lamp was determined from the ratio of the response of the pyrometer as it viewed the lamp to that as it viewed a Cu-fixed-point blackbody radiator.

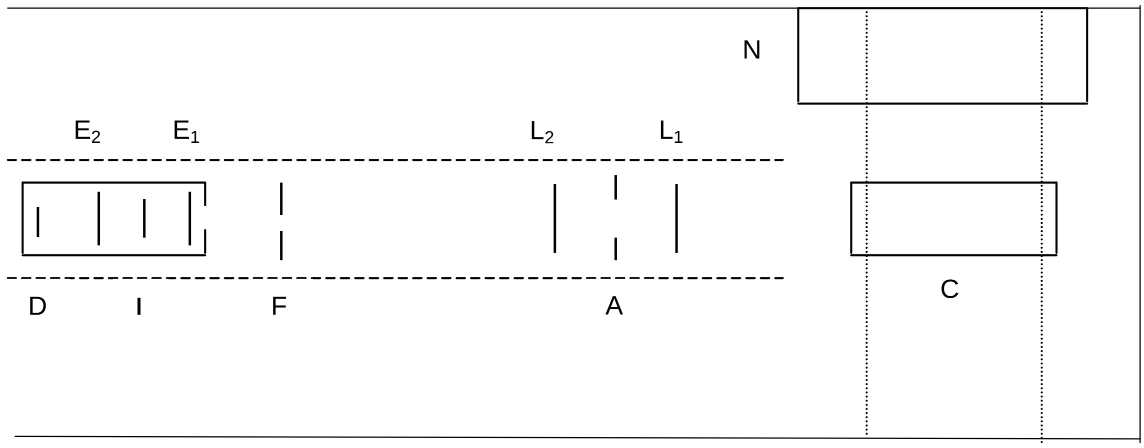



Fig. 4.1.1. Layout of the apparatus on an optical table (1222 mm × 2445 mm). N, furnace (305 mm dia., 610 mm long) embodying a blackbody radiator; C, carriage carrying a lamp mount for the lamp; S, scope temporarily in place for sighting at the notch of the lamp filament and the image of the field stop for adjusting the height of the notch of the filament to be the same as the image of the field stop; $L_1$ and $L_2$, matched pair of achromatic lenses (diameter and focal length, 69 mm and 500 mm respectively); A, aperture stop (either 65 mm dia. or 21 mm dia.); F, field stop (0.6 mm dia.); $E_1$ and $E_2$, pair of lenses; I, interference filter (nominal center wavelength and half width, 650 nm and 10 nm respectively); D, silicon photodiode (Hamamatsu S1226-5BQ) with ancillary electronic components (including a feedback resistor of 1 GΩ).

N and C are mounted on a pair of rails (dotted lines) to facilitate moving the blackbody radiator (housed inside N) or the lamp (mounted on C) to align with the optical axis.

$E_1$, $E_2$, I, and D are inside a brass housing having a copper coil for circulating temperature-controlled water. These components comprise our photoelectric detector. A blackened shroud (not shown) shields F from stray light.

$L_1$, A, $L_2$, F, $E_1$, I, $E_2$, and D are mounted on holders that are movable along an optical bench (2089 mm long, dashed lines) which lies perpendicular to the rails.

The components on the optical bench comprise our optical pyrometer. The common optical axis for these components is 360 mm above the optical table.

*- Formal definition/derivation of the spectral radiance temperature with explicit reference to corrections applied*

Above the freezing point of Ag, the ITS-90 is defined by the equation:

$$L_{b,\lambda}(T_x) \,/\, L_{b,\lambda}(T_0) = \{\exp(c_2\,\lambda^{-1}T_0^{-1}) - 1\} \,/\, \{\exp(c_2\,\lambda^{-1}T_x^{-1}) - 1\} \qquad (1)$$

where $T_0$ is any one of the (assigned) freezing points of Ag, Au and Cu, $T_x$ is the temperature on the ITS-90, $c_2$ = 0.014388 m · K, and $L_{b,\lambda}$ is the radiance of a blackbody (the Planck's function) at the wavelength $\lambda$ in vacuum.

The left-hand side of Eq. (1) is the ratio of monochromatic radiances. Our measurements, however, are the ratio of the integrated radiances:

$$\int_{\lambda_1}^{\lambda_2} \tau_\lambda s_\lambda L_{b,\lambda}(T_x)\,d\lambda \;/\; \int_{\lambda_1}^{\lambda_2} \tau_\lambda s_\lambda L_{b,\lambda}(T_0)\,d\lambda = G \qquad (2)$$

where the integration limits, $\lambda_1$ and $\lambda_2$, in our case are chosen to be 625 nm and 675 nm, respectively, $\tau_\lambda$ is the spectral transmittance of the interference filter, $s_\lambda$ is the spectral responsivity of the photo diode, and G is the ratio of the responses of the photoelectric detector as it sights on the blackbody radiators at temperatures $T_x$ and $T_0$, respectively.

Implicit in Eq. (2) is the assumption that the spectral transmittance for the glass lenses of the pyrometer is constant in the wavelength range of $\lambda_1$ and $\lambda_2$ so that it cancels from the equation.

With known $\tau_\lambda$, $s_\lambda$, $T_0$, and G, Eq. (2) can be solved for $T_x$ (in our case, by the method of successively approximating the true value by the mean of the upper and lower bounds which approach each other in successive iterations).

Eq. (2 ) can be rearranged as

$$\int_{\lambda_1}^{\lambda_2} \tau_\lambda s_\lambda L_{b,\lambda}(T_x)\,d\lambda = \int_{\lambda_1}^{\lambda_2} \tau_\lambda s_\lambda\, G\, L_{b,\lambda}(T_0)\,d\lambda. \qquad (3)$$

The integrals on both sides of this equation can be interpreted as the two separate areas under the curves of $\tau_\lambda s_\lambda L_{b,\lambda}(T_x)$ and $\tau_\lambda s_\lambda G L_{b,\lambda}(T_0)$ in a plot with varying $\lambda$ as the abscissa. A necessary condition for the two areas to be equal is that the curves must cross each other at least once at a specific wavelength $\lambda_e$ (the effective wavelength). At this wavelength, the ordinates, $\tau_\lambda s_\lambda L_{b,\lambda}(T_x)$ and $\tau_\lambda s_\lambda G\, L_{b,\lambda}(T_0)$, are equal and therefore $L_{b,\lambda e}(T_x) \,/\, L_{b,\lambda e}(T_0)$ = G. As a result, the ratio of the monochromatic radiances $L_{b,\lambda e}(T_x)$ and $L_{b,\lambda e}(T_0)$ in Eq. (1) is identical to the ratio of the integrated radiances in Eq. (2). The $T_x$ that satisfies Eq. (2) also satisfies Eq. (1) and therefore is a temperature on the ITS-90.

For $\lambda \le \lambda_2$ and $T_0 < T_x$, the ratio $L_{b,\lambda}(T_x) \,/\, L_{b,\lambda}(T_0)$ decreases monotonically with increasing $\lambda$. We can conclude that the condition of $L_{b,\lambda e}(T_x) \,/\, L_{b,\lambda e}(T_0)$ = G occurs only once at a unique $\lambda_e$.

For a non-blackbody such as the tungsten strip lamp, Eq. (2) becomes

$$\int_{\lambda_1}^{\lambda_2} \tau_\lambda s_\lambda L_\lambda(T_{x'})\,d\lambda \;/\; \int_{\lambda_1}^{\lambda_2} \tau_\lambda s_\lambda L_{b,\lambda}(T_0)\,d\lambda = G. \qquad (4)$$

where $T_{x'}$ is the true temperature of the non-blackbody and $L_\lambda(T_{x'})$ is its radiance. Since the definite integral of $L_{b,\lambda}(T)d\lambda$ increases monotonically with $T$, there is a blackbody of temperature $T_x$ having the same total radiance in the wavelength band between $\lambda_1$ and $\lambda_2$:

$$\int_{\lambda_1}^{\lambda_2} \tau_\lambda s_\lambda\, L_\lambda(T_{x'})\mathrm{d}\lambda = \int_{\lambda_1}^{\lambda_2} \tau_\lambda s_\lambda L_{\mathrm{b},\lambda}(T_x)\mathrm{d}\lambda\ . \tag{5}$$

The temperature $T_x$ of the substitute blackbody can be determined as discussed previously. It is defined to be the radiance temperature of the non-blackbody at the effective wavelength $\lambda_e$ which is obtained by solving Eq. (1) with known $T_x$.

### *4.1.2. Transfer of radiance temperatures to strip lamps*

*- Description of equipment and procedures, including corrections*

When we obtained the lamps from the manufacturer (GEC Hirst Research Centre), the copper lamp pins (posts) were not yet soldered into the copper blocks. During the soldering of the pins, we arranged that the bases of the blocks were leveled and the lamp filament was plumbed. Subsequently, the blocks were anchored to a glass plate (35 mm $\times$ 89 mm) which became the base of the lamp.

Thereafter, the levelness of the plate determines the vertical orientation of the lamp. For calibration, the lamp is placed upright on a level rotary table. The position of the lamp is adjusted so that the part of the filament embodying the notch is on the axis of rotation of the table. The height of the table is adjusted to bring the notch of the filament to the same level as the optical axis. Viewing along the optical axis from the lamp towards the pyrometer, we rotate the rotary table and translate it sideways as necessary until the center of the fiducial mark (a circular paint dot) on the lamp window lies midway between the vertical edges of the filament. The position of the lamp along the optical axis is determined by the method described in sub-section *3.2.1.2 "Focusing"* in [1] by determining the position where the apparent width of the lamp filament is a minimum.

Our home-made pyrometer (Fig. 4.1.1) employs an aperture stop of 65 mm diameter for temperature measurements ranging from 962 °C to 1400 °C. For temperatures from 1300 °C to 1700 °C, a smaller aperture of 21 mm diameter is used instead. Generally, changing a component of the pyrometer alters its characteristics. For simplicity, we consider that we have two pyrometers covering two overlapping temperature ranges. The size-of-source effect and non-linearity for each pyrometer is measured individually.

The photo current $i(t_{Cu})$ of each pyrometer, which targets the Cu blackbody, need be known. With the large aperture, the photo current $i(t_{Cu65})$ is sufficiently large (~ 0.5 nA) to be measured directly. With the small aperture, the photo current $i(t_{Cu21})$ is approximately 10 times smaller and is determined indirectly. When the copper ingot in the blackbody undergoes freezing or melting, we repeatedly interchange the aperture to obtain measurements of $i(t_{Cu65})$ and $i(t_{Cu21})$ Based on many measurements from different freezes and melts, the mean (β) of the ratio of $i(t_{Cu65})$ / $i(t_{Cu21})$ is computed ($\beta$ = 9.389 2 $\pm$ 0.001 7). In the calculation of the lamp temperature, the value of $i(t_{Cu21})$ is always obtained by dividing the measured $i(t_{Cu65})$ by β.

As discussed previously (Sec. 4.1.1, under the sub-title "*Formal definition/derivation of the spectral radiance temperature* ....."), the spectral radiance of the lamp is approximated by that of a blackbody at temperature $T_x$ which becomes the spectral radiance temperature of the lamp. Solution of Eq. (2) to obtain $T_x$ requires that the spectral transmittance $\tau_\lambda$ of the interference filter and the spectral responsivity $s_\lambda$ of the photodiode be known. These were measured separately (Appendix I).

Portions of the total response of the photodetector, which are due to radiation below $\lambda_1$ (625 nm) and above $\lambda_2$ (675 nm), should be accounted for. Taking the radiation source to be a blackbody at a temperature of 1357.77 K ($T_{Cu}$), we integrate (using Simpson's rule) the spectral response, $\tau_\lambda s_\lambda L_{b,\lambda}(T_{Cu})\, d\lambda$ in the three wavelength ranges of 400 nm to 624 nm, 624 nm to 676 nm, and 676 nm to 1100 nm. The three integrals are found to be in the ratio of $I_a : I_b : I_c$, respectively, where $I_a$ = 0.000 007, $I_b$ = 0.996 409, and $I_c$ = 0.003 584 (Appendix I). Since $I_a$ is relatively small, we consider the response due to radiation below $\lambda_1$ to be negligible. The total response should be reduced by a factor of 0.996 409 to obtain the desired response due to radiation in the chosen pass band of $\lambda_1$ to $\lambda_2$.

We also measured $I_b$ by using a sharp-cut colored glass filter (Schott) RG830. Its spectral transmittance is less than $10^{-6}$ for wavelengths up to $\lambda_2$, increases to 0.9061 at 940 nm, and remains constant to within $\pm$ 0.0005 for wavelengths up to 1300 nm where the transmittance measurement ends. The measured value for $I_b$ is 0.996 378. This differs insignificantly from the calculated value. The measured value was used to correct the photocurrent of our blackbody radiation source. The same glass filter was also used to determine the correction for the lamp at various temperatures.

### *4.2. Presentation of results*

#### *4.2.1. Local conditions to be specified*

##### *4.2.1.1. Reference thermometer*

- *Effective wavelength ($\lambda_e$) / local reference wavelength*

We calculate the unknown radiance temperature $T_x$ for each measured radiance ratio G by solving Eq. (2) with the reference temperature $T_0$ equal to $T_{Cu}$. Subsequently, the effective wavelength $\lambda_e$ is calculated by solving Eq. (1) for $\lambda$ with the known $T_x$.

- *Half-width of spectral response function*

This is nominally 10 nm.

- *Aperture ratio; f-number*

We interpret the aperture ratio to be the ratio of the diameters of the objective lens $L_1$ and the aperture stop A in Fig. 4.1.1. This is equal to 1.1 and 3.3 for the large and small aperture stops which cover the temperature ranges of 962 °C to 1400 °C and 1300 °C to 1700 °C, respectively.

The f-number is 7.7 and 24 for the temperature ranges mentioned above, respectively.

- *Target distance*

This is nominally 500 mm.

- *Target field dimensions*

This is a circular area of 0.6 mm diameter.

- *Size-of-source effect (SSE)*

This was measured for a circular source and for a rectangular source to simulate the conditions when the pyrometer views the blackbody furnace and the lamp (Appendix II).

- *Effective source diameter $\phi_d$ of the strip*

This does not concern us because the SSE is accounted for (see last paragraph).

*4.2.1.2. Transfer lamps*

- *Orientation of the lamp*

See Sec. *4.1.2 "Description of equipment and procedures, including corrections"*.

- *Nominal base temperature and its stability*

The temperature of the two copper blocks that comprise the base of the lamp was regulated by circulating water from a bath at a nominal temperature of 20°C. The minimum and maximum temperatures of the lamp base were 19.94 °C (lamp C598, 3rd run, 962 °C) and 20.89 °C (same lamp, 5th run, 1700 °C).

- *Total burning time*

This was not tallied. It will be reported if it is required.

*4.2.1.3. Ambient conditions*

- *$T_{amb}$,, RH; mean, maximum and minimum values*

The room temperature was normally 23 °C. The humidity was not recorded.

*4.2.2. Measurement results*

See Appendices XI and XII for a detailed reporting of the measurement results.

*4.3. Uncertainties*

No efforts were made to carefully classify the uncertainties into types A and B. Generally, repeated measurements are few. Vigorous statistical treatment may not be worthwhile. With three exceptions that are of type A ($k$ = 1) (uncertainty items labeled $s_{A13}$, $s_{A14}$, and $s_{A17}$), all of the uncertainties given below are considered to be of type B ($k$ = 1). They are assumed to be uncorrelated and are simply summed in quadrature. They are denoted by the symbols $s_{Bi}$ and $\rho_{Bi}$ for absolute and fractional uncertainties, respectively, where the subscript i denotes the component. For brevity the unit for the $s_{Bi}$ is normally not shown and is implicitly the kelvin.

*4.3.1. Identification of uncertainty components*

*I. Reference blackbody radiator*

*- Realization of the reference temperature*

*Subcomponents:*

*impurities*

Uncertainty in reference temperature based on data in Appendix III,

$s_{B1}$ : 0.004

*emissivity*

The emissivity is estimated to be 0.999 97 ± 0.000 03 ($\varepsilon \pm s_\varepsilon$) [2].

Uncertainty in the reference temperature calculated using Eq. (I) in Appendix IV with $T_x = T_{Cu}$ and $s_\varepsilon / \varepsilon$ = 0.000 03,

$s_{B2}$ : 0.002 5

*temperature difference ΔT across the bottom section of the cavity in view*

Estimation for $\Delta T$, based on [3], is –0.001 2 ± 0.000 5 K.

Uncertainty,

$s_{B3}$ : 0.000 5

Combined uncertainty ($s_{B1}$, $s_{B2}$, $s_{B3}$),

$s_{B4}$ : 0.004 7

Uncertainties propagated at various temperatures and calculated using Eq. (G) in Appendix IV,

$s_{B5}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.004 | 0.004 | 0.005 | 0.005 | 0.005 | 0.006 | 0.006 | 0.007 | 0.008 | 0.009 | 0.010 |

*II. Reference thermometer*

*II.1. Ratio of photo-currents*

-- *Photo current - measurement*

Fractional uncertainty in the measurements of radiance ratios due to the non-reproducibility (day-to-day variation) of the response of the detector when it views the blackbody radiator at the freezing point of copper (note that the uncertainty due to detector drift is embedded in this),

$\rho_{B6}$ : 0.002 5

Fractional uncertainty due to fluctuations (noise) of the detector reading,

$\rho_{B7}$ : This varies with temperature (Appendix V). The largest is 0.000 1 at 962°C.

-- *Photo current - resolution*

Uncertainties due to resolution (quantization) are negligible compared to the uncertainties due to fluctuations of readings.

Combined fractional uncertainty ($\rho_{B6}$, $\rho_{B7}$),

$\rho_{B8}$ : 0.002 5

Uncertainties propagated at various temperatures calculated using Eq. (J) in Appendix IV,

$s_{B8}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.172 | 0.183 | 0.202 | 0.208 | 0.213 | 0.245 | 0.280 | 0.316 | 0.335 | 0.396 | 0.440 |

-- *Linearity*

Fractional uncertainty (Appendix VI),

$\rho_{B9}$ : 0.000 04.

Uncertainties at various temperatures calculated using Eq. (J) in Appendix IV,

$s_{B9}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.004 | 0.004 | 0.005 | 0.006 | 0.006 | 0.007 |

*II.2. Size of source effect (SSE)*

Fractional uncertainty (based on the data in Appendix II),

$\rho_{B10}$ : 0.000 15.

Uncertainties at various temperatures calculated using Eq. (J) in Appendix IV,

$s_{B10}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.010 | 0.011 | 0.012 | 0.012 | 0.013 | 0.015 | 0.017 | 0.019 | 0.021 | 0.024 | 0.026 |

*II.3. spectral parameters*

-- *Spectral response function, including (especially) the spectral transmission of the interference filter and the spectral responsivity of the detector. Stability of the interference filter*

Uncertainty in the wavelength measurement of the filter transmittance is estimated to be 0.1 nm,

Uncertainties at various temperatures calculated by using Eq. (H) in Appendix IV,

$s_{B11}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.017 | 0.012 | 0.003 | 0.000 | 0.002 | 0.019 | 0.038 | 0.060 | 0.084 | 0.109 | 0.138 |

Uncertainty in detector responsivity:

---- negligible.

The uncertainty in the detector responsivity $s_\lambda$ can be due to the uncertainty in the wavelength measurements. This is considered to be accounted for by the uncertainty $s_{B11}$. The uncertainty in $s_\lambda$ can be due to the uncertainty in the measurement of the magnitude of $s_\lambda$, which affects the slope $ds_\lambda/d\lambda$. This uncertainty in $s_\lambda$ is estimated to be negligible [4].

Uncertainty due to the stability of the interference filter:

----- assumed negligible.

-- *Blocking*

$\rho_{B12}$ : 0.000 03

This is based on the difference between the fractional correction by calculation for the radiation transmission (0.996 41) and that by measurement (0.996 38) (see Sec. *4.1. "Description of equipment and procedures, including corrections"*).

Uncertainties at various temperatures calculated using Eq. (J) in Appendix IV,

$s_{B12}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.002 | 0.002 | 0.002 | 0.002 | 0.003 | 0.003 | 0.003 | 0.004 | 0.004 | 0.005 | 0.005 |

-- *Mean effective wavelength ($\lambda_e$), a variable, linking up additionally with the spectral characteristics of the transfer lamps around the fixed reference wavelengths $\lambda_{rl}$ (local value) and $\lambda_r$ (reference value)*

----- partly negligible and partly accounted for.

The mean effective wavelength is computed according to the spectral response function. The computation itself is practically exact. Uncertainty due to the measured values in the spectral function is accounted for by the uncertainties in filter transmittance ($s_{B11}$, $s_{B12}$) and detector responsivity (negligible).

*II.4. Possible additional parameters*

-- *Transmission of neutral density filter(s)*

We did not use a neutral density filter to reduce the radiant flux. Instead, we use a smaller entrance aperture. For the blackbody source which is of concern, the reduction is given by 1/β where β = 9.389 2 ± 0.001 7 (see Sec. *4.1.2 "Description of equipment and procedures, including corrections"*.)

Fractional uncertainty on the reduction

$\rho_{A13}$ : 0.000 18

Uncertainties at various temperatures calculated by using Eq. (J) in Appendix IV,

$s_{A13}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.012 | 0.013 | 0.015 | 0.015 | 0.016 | 0.018 | 0.020 | 0.023 | 0.026 | 0.029 | 0.032 |

As shown in the measurement results (Sec. *4.2.2*), the calibrations based on the large and the small apertures generally differ in the overlapping temperature range of 1300 °C and 1400 °C. The standard deviations of the residuals resulting from curve fitting are 0.122 °C at 1300 °C and 0.139 °C at 1400 °C (see later Sec. *III.1. Lamp current* -- *Lamp currents $I_j$ as prescribed*). Under the assumption that the uncertainty in each of the two calibrations based on the two apertures is 0.130 °C at 1350 °C, the uncertainties at other temperatures, calculated by substituting 1623.15 K for $T_{Cu}$ and 0.130 K for $s_{TCu}$ in Eq. (G) in Appendix IV, are assumed to be:

$s_{A14}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.075 | 0.080 | 0.088 | 0.091 | 0.093 | 0.107 | 0.122 | 0.138 | 0.155 | 0.173 | 0.192 |

Combined uncertainty ($s_{A13}$, $s_{A14}$)

$s_{A15}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.076 | 0.081 | 0.089 | 0.092 | 0.094 | 0.109 | 0.124 | 0.140 | 0.157 | 0.175 | 0.195 |

-- *Absorption by water vapour ( $\lambda_r \cong 950$ nm)*

Our $\lambda_r$ is 650 nm.

*III. Transfer lamps*

*III.1. Lamp current*

-- *Lamp currents $I_\lambda$ as set*

The resistance of the standard resistor used for the measurement of lamp current is estimated to be 0.010 004 36 ± 0.000 000 01 Ω (based on data in Appendix VII).

Fractional uncertainty in the absolute value of the measured current,

$\rho_{B16}$ : $10^{-6}$

Fractional uncertainties in lamp current due to fluctuations in its measurement,

$\rho_{B17}$ : shown in Appendix VIII and tabulated below

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
| Fractional uncertainty/$10^{-6}$ | 4.7 | 4.0 | 3.5 | 3.3 | 3.2 | 2.7 | 2.4 | 2.2 | 2.1 | 2.0 | 2.0 |

Combined fractional uncertainties ($\rho_{B16}$, $\rho_{B17}$),

$\rho_{B18}$ :

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
| Fractional uncertainty/$10^{-6}$ | 4.8 | 4.1 | 3.6 | 3.4 | 3.4 | 2.9 | 2.6 | 2.4 | 2.3 | 2.2 | 2.2 |

Analytical expression for the average of the calibrations of lamps 644C and C598 (Eq. 13 in Table B3 under Sec. *4.2.2 "Measurement results"* for each of the two lamps):

$t_\lambda$ / °C = 1373.4084 + 349.9584 $z$ – 36.7109 $z^2$ + 17.3425 $z^3$ – 9.8311 $z^4$ + 0.8960 $z^5$ – 5.6400 $z^6$ + 6.5661 $z^7$

where $z = (I$ / A – 9) / 4 and $I$ is lamp current.

$(\mathrm{d}t_\lambda/\mathrm{d}I)$ / (°C / A) = (349.9584 – 73.4218 $z$ + 52.0275 $z^2$ – 39.3244 $z^3$ + 4.4800 $z^4$ – 33.8400 $z^5$ + 45.9627 $z^6$) / 4

Average of reference currents $I_j$ (in Table A1 for each of the two lamps):

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Avg. current / A | 5.106 | 5.378 | 5.887 | 6.061 | 6.196 | 7.139 | 8.184 | 9.311 | 10.505 | 11.758 | 13.064 |
| Nom.Temp. / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
| $(\mathrm{d}t_\lambda/\mathrm{d}I)$ / (°C / A) | 145 | 134 | 120 | 116 | 113 | 100 | 92 | 86 | 82 | 78 | 77 |

Uncertainties in $t_\lambda$ due to the uncertainties in the absolute value of the lamp current based on the sensitivity $\mathrm{d}t_\lambda/\mathrm{d}I$, average reference currents $I_j$, and fractional uncertainty $\rho_{B18}$ given above ($\Delta t = \mathrm{d}t_\lambda/\mathrm{d}I \cdot I_j \cdot \rho_{B18}$)

$s_{B18}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.004 | 0.003 | 0.003 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |

-- *Lamp currents $I_j$ as prescribed*

In the calculation to determine the lamp calibration we did not adjust the set currents to bring them equal to the reference currents. We obtained the calibration by fitting an analytical expression of temperature vs. set current (see Table B3 in Sec. *4.2.2 "Measurement results*"). In place of the uncertainties due to current adjustments, we have the uncertainties stemming from curve fitting. We assume that these uncertainties are indicated by the residuals (computed temperature – measured temperature) (see Appendix IX). The uncertainties are

$s_{A19}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertainty | 0.024 | 0.025 | 0.020 | 0.031 | 0.041 | 0.040 | 0.122 | 0.139 | 0.028 | 0.031 | 0.037 |

*III.2. Radiance temperature*

-- *Short-term stability*

This is assumed to be negligible in comparison with the non-reproducibility of the response of the detector at the reference fixed point.

-- *Drift*

No study was made.

-- *Dependence on wavelength: $T_\lambda = T_\lambda(\lambda)$; $dT_\lambda/d\lambda(\lambda)$*

Fractional uncertainty in $dT_\lambda/d\lambda$ [1],

$\rho_{B20}$ : 0.1

Uncertainties in the wavelength corrections in Table B1 (using Eq. D in Appendix IV),

$s_{B20}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\lvert\Delta t\rvert$ / °C | 0.004 | 0.003 | 0.002 | 0.002 | 0.002 | 0.000 | 0.002 | 0.004 | 0.007 | 0.009 | 0.013 |
| Uncertainty | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 |

-- *Dependence on base temperature $T_\lambda = T_\lambda(\lambda; T_b)$*

Uncertainties in the corrections for the temperature of the lamp base in Table B2 (see Appendix X),

$s_{B21}$ :

| $t$ / °C | 962 | 1000 | 1064 | 1085 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Largest $\lvert\Delta t_b\rvert$ / °C | 0.305 | 0.320 | 0.336 | 0.361 | 0.351 | 0.418 | 0.489 | 0.579 | 0.665 | 0.752 | 0.886 |
| Uncertainty in $dt_\lambda / dt_b$ | 0.016 | 0.013 | 0.012 | 0.010 | 0.009 | 0.007 | 0.005 | 0.003 | 0.000 | 0.000 | 0.000 |
| Uncertainty in $\Delta t_\lambda$ correction | 0.005 | 0.004 | 0.004 | 0.004 | 0.003 | 0.003 | 0.002 | 0.002 | 0.000 | 0.000 | 0.000 |

*Residual parameters:*

-- *Alignment (spatial and angular distribution of radiance)*

spatial : axial position (along optical axis) ---- negligible.

With the procedure of photoelectric focusing (Sec. *3.2.1.2*), the lamp filament can be positioned at the focal point to within ±0.2 mm along the optical axis. The uncertainty associated with focusing is negligible.

lateral position (normal to optical axis on a horizontal plane) ---- negligible.

After alignment, the lamp can be moved laterally for 0.2 mm without causing the detector response to taper off. Under the assumption that the micrometer drive can reproducibly set the lateral position of the lamp within ±0.01 mm, the uncertainty associated with the lateral position is negligible.

vertical position ---- assumed negligible.

We did not measure the vertical temperature gradient of the lamp filament. With a telescope, however, we observed (in the K5 Comparison) that the notch of the lamp filament was probably at a level within ±0.05 mm of the optical axis at all temperature measurements. Temperature variation along such a small region is expected to be negligible.

angular orientation on a horizontal plane

Within a run, the angular orientation is reproducible to within ±5'. If, by assumption, the directional radiance distribution follows the cosine law, the fractional uncertainty is $10^{-6}$ and is negligible.

-- *Target field*

Assumed negligible (the target field is always properly filled).

-- *Cleaning of the window*

Assumed negligible.

*IV. Lamp-thermometer composite parameters*

-- *Radiance temperature* $T_\lambda = T_\lambda(\lambda_e; T_b)$ (before corrections, Table A1)

| Index | Temperature | 4.3. Uncertainties | | | | | | Combined |
|---|---|---|---|---|---|---|---|---|
| | | *I. Blackbody radiator* | *II. Thermometer* | | | | *III. Lamp* | |
| | | *I* | *II.1* | *II. 3* | *II. 3* | *II. 4* | *III.1* | |
| | | $s_{B5}$ | $s_{B8}$ | $s_{B11}$ | $s_{B12}$ | $s_{A15}$ | $s_{B18}$ | |
| 1 | 962 | 0.004 | 0.172 | 0.017 | 0.002 | 0.076 | 0.004 | 0.189 |
| 2 | 1000 | 0.004 | 0.183 | 0.012 | 0.002 | 0.081 | 0.003 | 0.201 |
| 3 | 1064 | 0.005 | 0.202 | 0.003 | 0.002 | 0.089 | 0.003 | 0.221 |
| 4 | 1085 | 0.005 | 0.208 | 0.000 | 0.002 | 0.092 | 0.002 | 0.228 |
| 5 | 1100 | 0.005 | 0.213 | 0.002 | 0.003 | 0.094 | 0.002 | 0.233 |
| 6 | 1200 | 0.006 | 0.245 | 0.019 | 0.003 | 0.109 | 0.002 | 0.269 |
| 7 | 1300 | 0.006 | 0.280 | 0.038 | 0.003 | 0.124 | 0.002 | 0.309 |
| 8 | 1400 | 0.007 | 0.316 | 0.060 | 0.004 | 0.140 | 0.002 | 0.351 |
| 9 | 1500 | 0.008 | 0.355 | 0.084 | 0.004 | 0.157 | 0.002 | 0.397 |
| 10 | 1600 | 0.009 | 0.396 | 0.109 | 0.005 | 0.175 | 0.002 | 0.447 |
| 11 | 1700 | 0.010 | 0.440 | 0.138 | 0.005 | 0.195 | 0.002 | 0.501 |

-- $T_\lambda := T_\lambda(\lambda_e; T_b)$, *corrected for the SSE* (Table A2)

| Index | Temperature | 4.3. Uncertainties* | | |
|---|---|---|---|---|
| | | Last table | *II. Thermometer* | Combined |
| | | | *II.2* | |
| | | | $s_{B10}$ | |
| 1 | 962 | 0.189 | 0.010 | 0.189 |
| 2 | 1000 | 0.201 | 0.011 | 0.201 |
| 3 | 1064 | 0.221 | 0.012 | 0.221 |
| 4 | 1085 | 0.228 | 0.012 | 0.228 |
| 5 | 1100 | 0.233 | 0.013 | 0.233 |
| 6 | 1200 | 0.269 | 0.015 | 0.269 |
| 7 | 1300 | 0.309 | 0.017 | 0.309 |
| 8 | 1400 | 0.351 | 0.019 | 0.352 |
| 9 | 1500 | 0.397 | 0.021 | 0.398 |
| 10 | 1600 | 0.447 | 0.024 | 0.448 |
| 11 | 1700 | 0.501 | 0.026 | 0.502 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

-- $T_\lambda := T_\lambda(\lambda_e; T_b)$, *corrected for SSE and non-linearity* (Table A3)

| Index | Temperature | 4.3. Uncertainties* | | |
|---|---|---|---|---|
| | | Last table | *II. Thermometer* | Combined |
| | | | *II.2* | |
| | | | $S_{B9}$ | |
| 1 | 962 | 0.189 | 0.003 | 0.189 |
| 2 | 1000 | 0.201 | 0.003 | 0.201 |
| 3 | 1064 | 0.221 | 0.003 | 0.221 |
| 4 | 1085 | 0.228 | 0.003 | 0.228 |
| 5 | 1100 | 0.233 | 0.003 | 0.233 |
| 6 | 1200 | 0.269 | 0.004 | 0.269 |
| 7 | 1300 | 0.309 | 0.004 | 0.309 |
| 8 | 1400 | 0.352 | 0.005 | 0.352 |
| 9 | 1500 | 0.398 | 0.006 | 0.398 |
| 10 | 1600 | 0.448 | 0.006 | 0.448 |
| 11 | 1700 | 0.502 | 0.007 | 0.502 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

*Conversion to reference conditions:*

-- $T_\lambda := T_\lambda(\lambda_e; T_{b;} I_\varnothing)$, *corrected to RH = 0% (only if* $\lambda_r = 950$ *nm)*

Non-applicable.

-- *Reference wavelength* $\lambda_r$: $T_\lambda := T_\lambda(\lambda_r; T_{b;} I_\varnothing)$ (Table B1)

| Index | Temperature | 4.3. Uncertainties* | | |
|---|---|---|---|---|
| | | Last table | *III. Lamp* | Combined |
| | | | *III.2* | |
| | | | $S_{B20}$ | |
| 1 | 962 | 0.189 | 0.003 | 0.189 |
| 2 | 1000 | 0.201 | 0.003 | 0.201 |
| 3 | 1064 | 0.221 | 0.002 | 0.221 |
| 4 | 1085 | 0.228 | 0.002 | 0.228 |
| 5 | 1100 | 0.233 | 0.001 | 0.233 |
| 6 | 1200 | 0.269 | 0.000 | 0.269 |
| 7 | 1300 | 0.309 | 0.001 | 0.309 |
| 8 | 1400 | 0.352 | 0.002 | 0.352 |
| 9 | 1500 | 0.398 | 0.003 | 0.398 |
| 10 | 1600 | 0.448 | 0.003 | 0.448 |
| 11 | 1700 | 0.502 | 0.004 | 0.502 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

-- *Base temperature 20$^{O}$C:* $T_\lambda := T_\lambda(\lambda_r; 20; I_0)$ (Table B2)

| Index | Temperature | 4.3. Uncertainties* | | |
|---|---|---|---|---|
| | | Last table | *III. Lamp* | Combined |
| | | | *III.2* | |
| | | | $S_{B21}$ | |
| 1 | 962 | 0.189 | 0.016 | 0.189 |
| 2 | 1000 | 0.201 | 0.013 | 0.201 |
| 3 | 1064 | 0.221 | 0.012 | 0.221 |
| 4 | 1085 | 0.228 | 0.010 | 0.228 |
| 5 | 1100 | 0.233 | 0.009 | 0.233 |
| 6 | 1200 | 0.269 | 0.007 | 0.269 |
| 7 | 1300 | 0.309 | 0.005 | 0.309 |
| 8 | 1400 | 0.352 | 0.003 | 0.352 |
| 9 | 1500 | 0.398 | 0.000 | 0.398 |
| 10 | 1600 | 0.448 | 0.000 | 0.448 |
| 11 | 1700 | 0.502 | 0.000 | 0.502 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

-- *Lamp current* $I_j$: $T_\lambda := T_\lambda(\lambda_r; 20; I_j)$ (Table B3)

| Index | Temperature | 4.3. Uncertainties* | | |
|---|---|---|---|---|
| | | Last table | *III. Lamp* | Combined |
| | | | *III.1* | |
| | | | $S_{A19}$ | |
| 1 | 962 | 0.189 | 0.024 | 0.191 |
| 2 | 1000 | 0.201 | 0.025 | 0.203 |
| 3 | 1064 | 0.221 | 0.020 | 0.222 |
| 4 | 1085 | 0.228 | 0.031 | 0.230 |
| 5 | 1100 | 0.233 | 0.041 | 0.237 |
| 6 | 1200 | 0.269 | 0.040 | 0.272 |
| 7 | 1300 | 0.309 | 0.122 | 0.333 |
| 8 | 1400 | 0.352 | 0.139 | 0.378 |
| 9 | 1500 | 0.398 | 0.028 | 0.399 |
| 10 | 1600 | 0.448 | 0.031 | 0.449 |
| 11 | 1700 | 0.502 | 0.037 | 0.503 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

*4.3.2. Specifying uncertainties*

*4.3.2.1. Representation*

*Uncertainties have to be specified in accordance with the 'Guide to the expression of uncertainty in measurement', co-edited by BIPM (1993), in terms of the (effective) standard deviations sA(i), sB(i), s(i), for the components i to be taken into consideration. The terms to be included in the propagation of uncertainties should be fully described.*

*4.3.2.2. Final specifications*

-- *Uncertainty components arranged within the framework given in 4.3.1.*

Already presented in Sec. *4.3.1*.

-- *The uncertainties* $s\{T_{\lambda}(\lambda_r; I_j)\}$ *vs.* $I_j$ *in the specified reference conditions (3.1.2),* $I_j$ *referring to the currents defined in Appendix D.* (See the reference currents in Table I in this report.)

| Index | Nominal temperature / °C | Lamp 644C | Lamp C598 | Uncertainty / K* |
|---|---|---|---|---|
| | | Current / A | | |
| 1 | 962 | 5.185 | 5.027 | 0.191 |
| 2 | 1000 | 5.457 | 5.298 | 0.203 |
| 3 | 1064 | 5.966 | 5.808 | 0.222 |
| 4 | 1085 | 6.141 | 5.981 | 0.230 |
| 5 | 1100 | 6.276 | 6.116 | 0.237 |
| 6 | 1200 | 7.223 | 7.054 | 0.272 |
| 7 | 1300 | 8.276 | 8.092 | 0.333 |
| 8 | 1400 | 9.411 | 9.210 | 0.378 |
| 9 | 1500 | 10.617 | 10.393 | 0.399 |
| 10 | 1600 | 11.880 | 11.635 | 0.449 |
| 11 | 1700 | 13.197 | 12.930 | 0.503 |

* The uncertainties of the NRC measurements have been slightly revised due to a mistake found by an external referee

## References

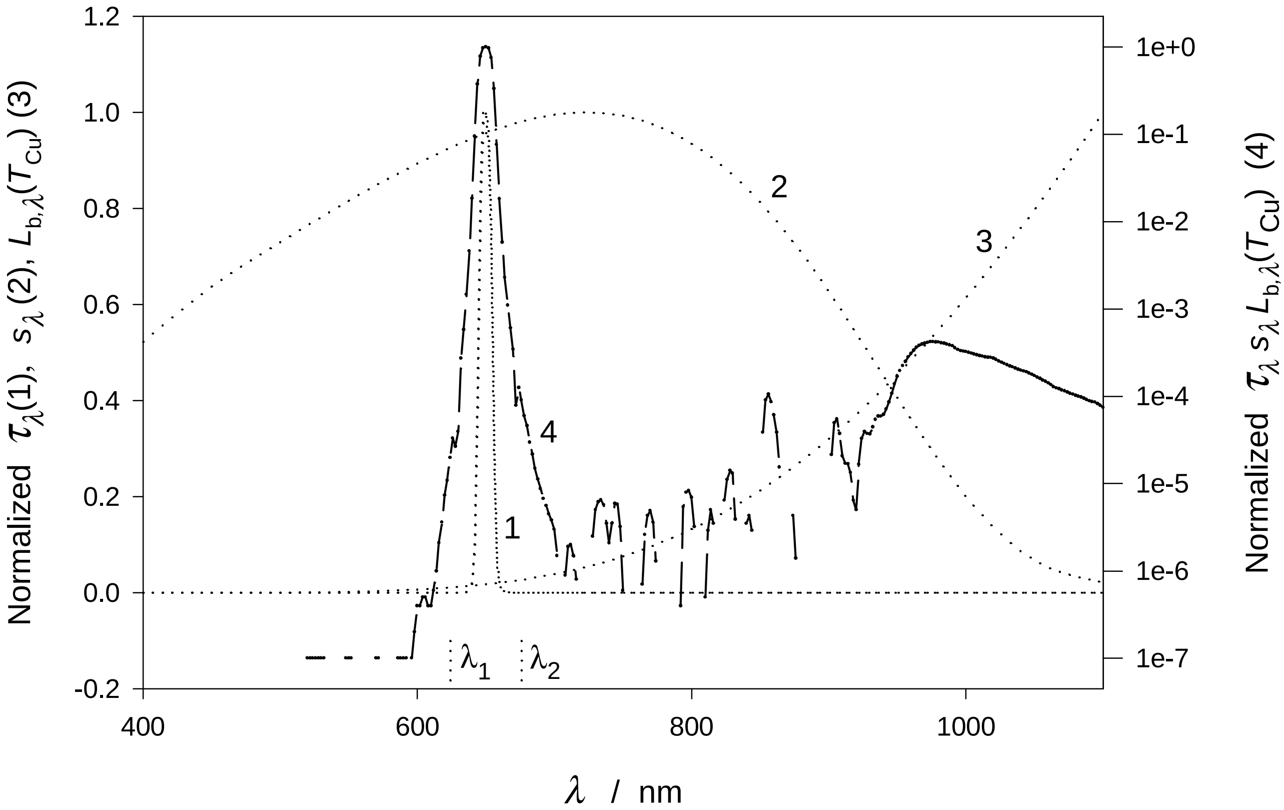

1. Bloembergen P., “Protocol to the local realizations of the ITS-90 between the silver point and 1700°C using vacuum tungsten-strip lamps as transfer standards”, 1 June 1997.

2. Ohtsuka M., Bedford R.E., “Measurement of the thermodynamic temperature interval between the freezing points of silver and copper”, in *Temperature, Its Measurement and Control in Science and Industry*, 1982, vol. 5, 175-181.

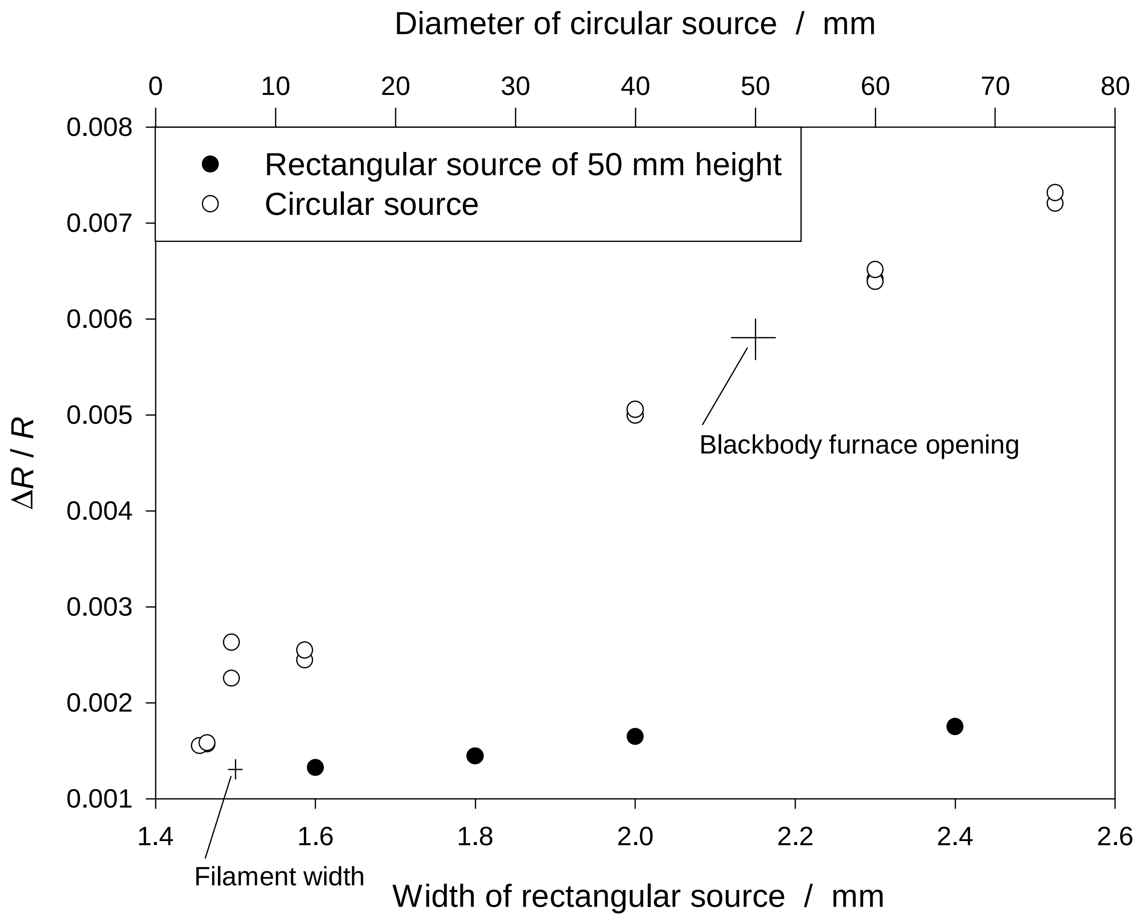
3. Ma C.K., “Experimental investigation of the temperature drop across the wall of a copper-freezing-point blackbody”, in *Temperature, Its Measurement and Control in Science and Industry*, 2002, vol. 7, 651-656.

4. Bedford R.E., Ma C.K., “Effect of uncertainties in detector responsivity on thermodynamic temperatures measured with an optical pyrometer”, *High Temperatures-High Pressures*, 1983, **15**, 119-130.

**Appendix I.** Spectral transmittance of the interference filter $\tau_\lambda$, spectral response $s_\lambda$ of the photo diode, and Planck's blackbody radiation function $L_{b,\lambda}(T_{Cu})$



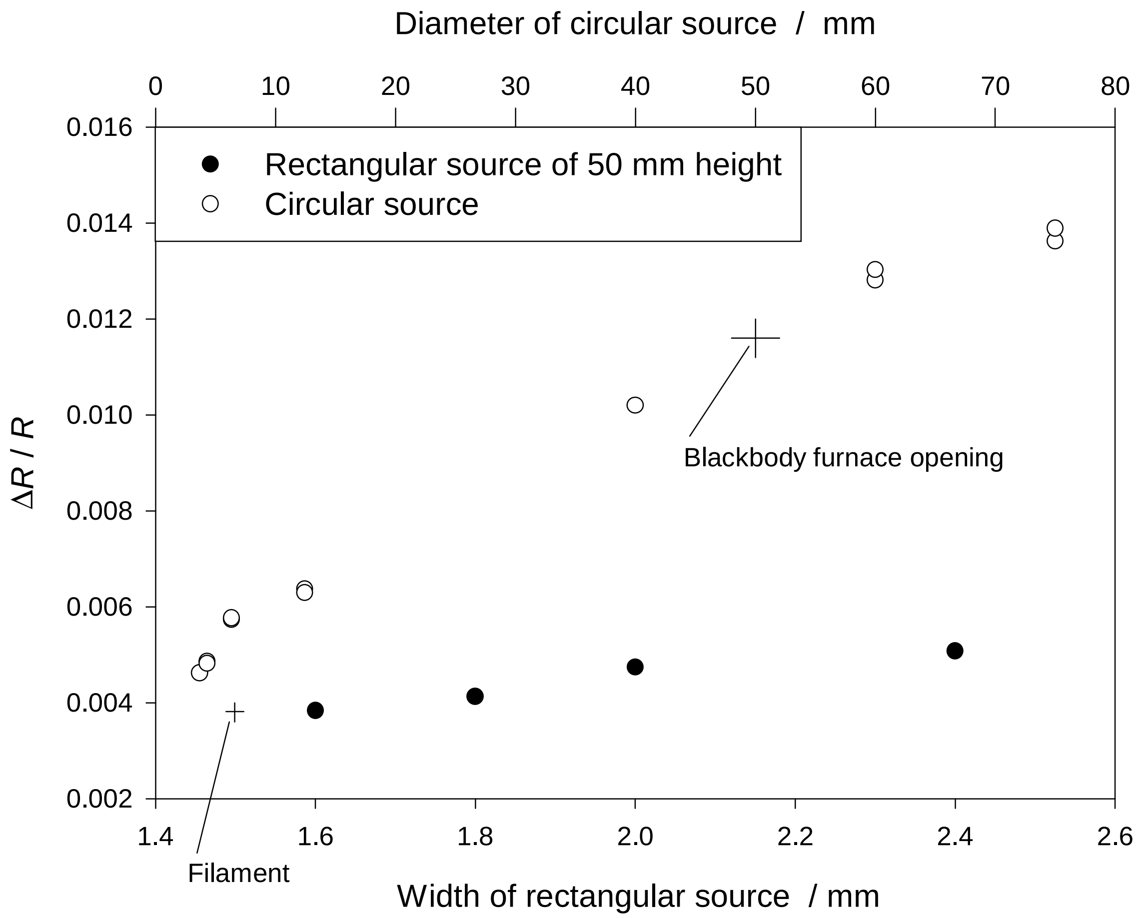
**Appendix IIa.** SSE for the pyrometer with the large aperture of 65 mm dia.




Size-of-source effect expressed as $\Delta R / R$ where $R$ is the total response of the pyrometer and $\Delta R$ is that part of the response due to radiation outside the target field.

Diameter of the opening of the blackbody furnace is 50 mm. The filament of the lamp is 1.5 mm wide, 50 mm long and 0.07 mm thick.

**Appendix IIb.** SSE for the pyrometer with the small aperture of 21 mm dia.




Size-of-source effect expressed as $\Delta R/R$ where $R$ is the total response of the pyrometer and $\Delta R$ is that part of the response due to radiation outside the target field.

Diameter of the opening of the blackbody furnace is 50 mm. The filament of the lamp is 1.5 mm wide, 50 mm long and 0.07 mm thick.

**Appendix III**. Temperature depressions due to impurities.

The thermometric metal used to fill the Cu fixed-point cells for this work and for the experiment in [2] are from the same batch. We have not analyzed the impurity contents for the cells in this work. However, the analysis for the cell in [2], which is taken to be a representative for our cells, is as follows:

| Impurity | Concentration by weight / $10^{-6}$ As received | Used |
|---|---|---|
| Ni | ----- | 9.4 |
| Cr | 0.037 | 4.5 |
| Fe | 0.58 | 3.3 |
| Si | 0.028 | 0.39 |
| Al | 0.15 | 0.043 |
| Pb | ----- | ----- |
| Mg | 0.21 | 0.16 |

We note that the concentrations for the first three items in the table above increased markedly after using the cell inside a heat pipe. These items are the major components of Inconel (72% Ni, 15.5% Cr, 8% Fe) which is the wall material of the heat pipe. We speculate that the increase in concentration is due to contamination that originates from the heat pipe.

We do not have precise knowledge of the net effect on the freezing temperature (precisely, liquidus point) of a high-purity alloy due to a multitude of impurities. A crude assumption is that they act independently and that their effects superimpose upon one another additively. Using the phase diagrams for binary alloys, we estimate them as follows:

| Impurity | Concentration / $10^{-6}$ | Temperature elevation / K |
|---|---|---|
| Ni | 9.4 | 0.003 5 |
| Cr | 4.5 | 0 |
| Fe | 3.3 | 0 |
| Si | 0.39 | –0.000 15 |
| Al | 0.043 | –0.000 01 |
| Pb | ----- | 0 |
| Mg | 0.16 | –0.003 |

Arithmetic sum ~ 0

Considering that the impurity concentrations of our thermometric copper samples were not known and the major temperature elevation in the table above is 0.0035 K, we assume that the uncertainty due to impurities is 0.004 K.

**Appendix IV**. Uncertainties in the calculated temperature due to the uncertainties in various factors affecting the calculation.

Using Wien's radiation law, we express the ratio of the radiance of a blackbody at $T_x$ to the radiance of the reference blackbody radiator at $T_{Cu}$ as

$$G = L_\lambda(T_x) / [\varepsilon\, L_\lambda(T_{Cu})] = \exp(c_2\, \lambda^{-1} T_{Cu}^{-1}) / [\varepsilon \exp(c_2 / \lambda^{-1} T_x^{-1})] \qquad \text{(A)}$$

where $\lambda$ is the reference wavelength (650 nm), $T_{Cu}$ is the copper blackbody temperature (1357.77 K), and $\varepsilon$ is the estimated emissivity of the blackbody radiator (0.999 97±0.000 03, [2]).

From Eq. (A) we obtain

$$T_x^{-1} = T_{Cu}^{-1} - \lambda\ c_2^{-1} \ln(\varepsilon G). \qquad \text{(B)}$$

The various partial derivatives of the above equation are

$$\partial T_x / \partial T_{Cu} = T_x^2\ T_{Cu}^{-2} \qquad \text{(C)}$$

$$\partial T_x / \partial \lambda = T_x^2\ c_2^{-1} \ln(\varepsilon G) \qquad \text{(D)}$$

$$\partial T_x / \partial \varepsilon = T_x^2\, c_2^{-1}\, \lambda\ \varepsilon^{-1} \qquad \text{(E)}$$

$$\partial T_x / \partial G = T_x^2\, c_2^{-1}\, \lambda\ G^{-1}. \qquad \text{(F)}$$

It follows that the uncertainties in $T_x$ due to the uncertainties in $T_{Cu}$, $\lambda$, $\varepsilon$, and G are, respectively,

$$s_{Tx,\,TCu} = T_x^2\ T_{Cu}^{-2}\ s_{TCu} \qquad \text{(G)}$$

$$s_{Tx,\,\lambda} = T_x^2\ c_2^{-1} \ln(\varepsilon G)\ s_\lambda \qquad \text{(H)}$$

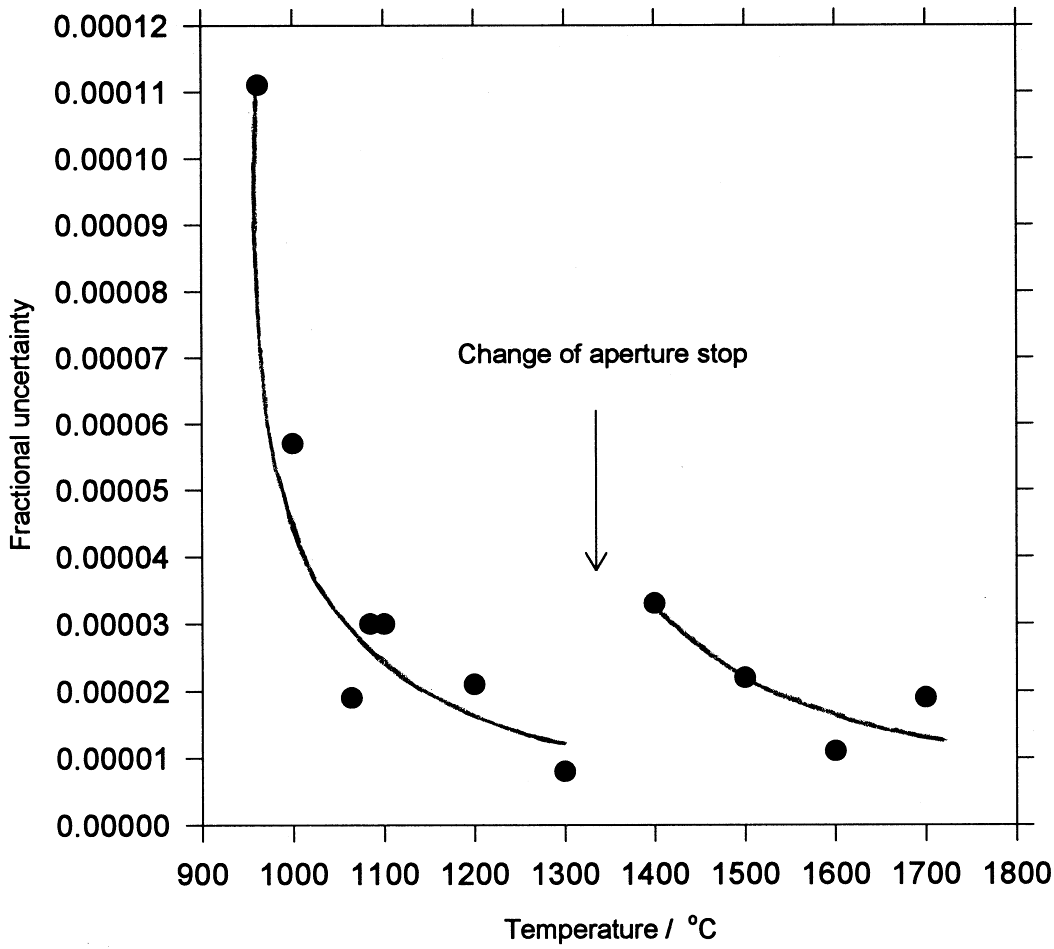
$$s_{Tx,\,\varepsilon} = T_x^2\, c_2^{-1}\, \lambda\ \rho_\varepsilon \quad \text{where the fractional uncertainty } \rho_\varepsilon = s_\varepsilon\, \varepsilon^{-1} \qquad \text{(I)}$$

$$s_{Tx,\,G} = T_x^2\, c_2^{-1}\, \lambda\ \rho_G \quad \text{where the fractional uncertainty } \rho_G = s_G\, G^{-1}. \qquad \text{(J)}$$

where s denotes the uncertainty and the subscripts $T$Cu, $\lambda$, $\varepsilon$, and G denote the contributing components.

An uncertainty in the detector reading may be due to the fluctuations of the reading itself or the positioning of the lamp, etc. This results in an uncertainty in the radiance ratio and in turn an uncertainty in the calculated temperature. Similarly, uncertainties in the correction factors for linearity and SSE result in uncertainties in the deduced radiance ratios and in turn the calculated temperatures. In all of these cases, Eq. (J) can be applied by using the appropriate fractional uncertainty $s_G\, G^{-1}$is in the equation.

**Appendix V**. Fractional uncertainties in detector readings due to fluctuations.



**Appendix VIa.** Non-linearity of the large aperture

○ experimental data points for a function
$F_L = 2i(\phi/2) / i(\phi)$ for $\phi >= 2\,\phi_{Cu}$
$= 1$ for $\phi = \phi_{Cu}$
$= i(2\phi) / 2i(\phi)$ for $\phi <= \phi_{Cu} / 2$ where i and $\phi$ are photo current and flux, respectively

□ data points from a hand-drawn curve (not shown) for $F_L$

........ analytical expression for $F_L$ obtained by fitting a curve to the data points from the hand-drawn curve

◆ correction factors $F_{NL}$ for the non-linearity obtained by calculation based on the expression for $F_L$

—— expression for $F_{NL}$

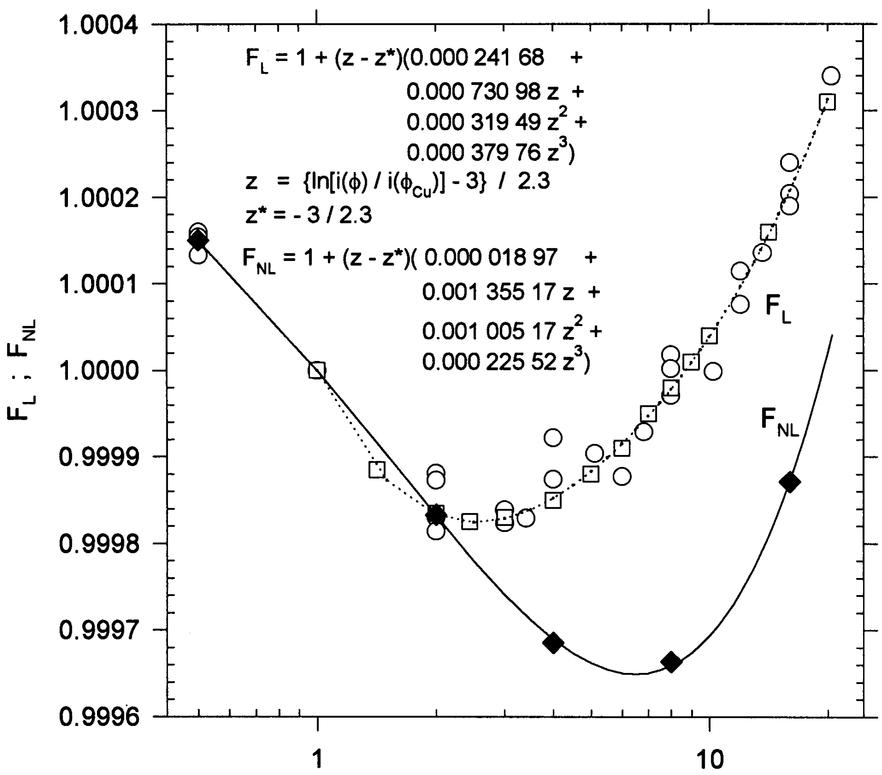
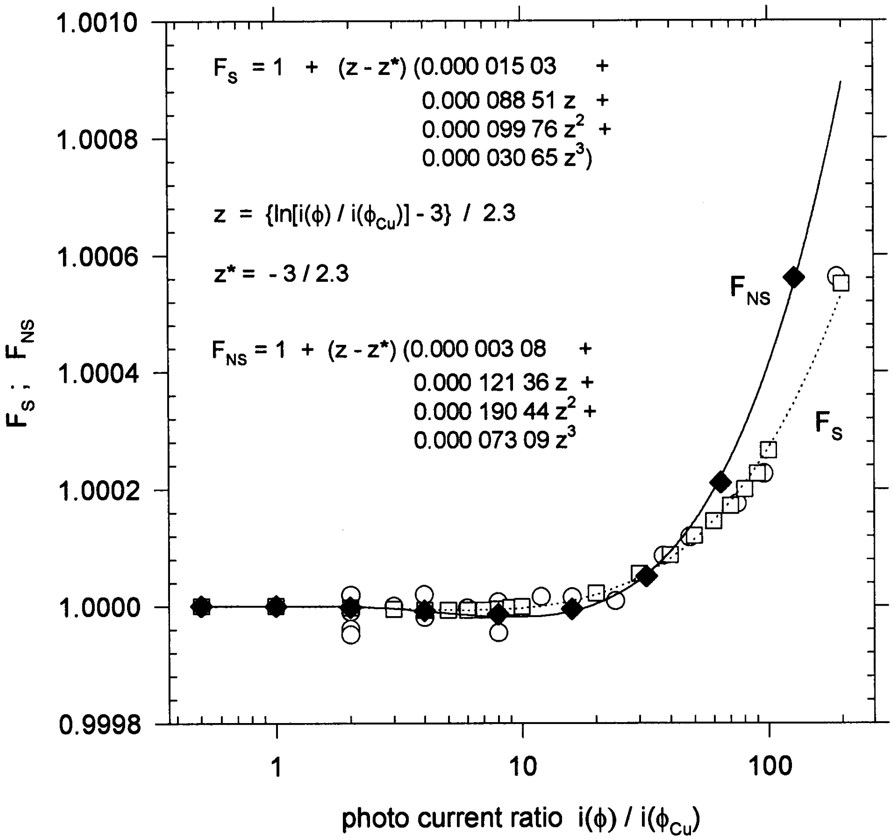



photo current ratio $i(\phi) / i(\phi_{Cu})$

where $i(\phi)$ and $i(\phi_{Cu})$ are the photo currents when the pyrometer targets the lamp and the Cu blackbody, respectively

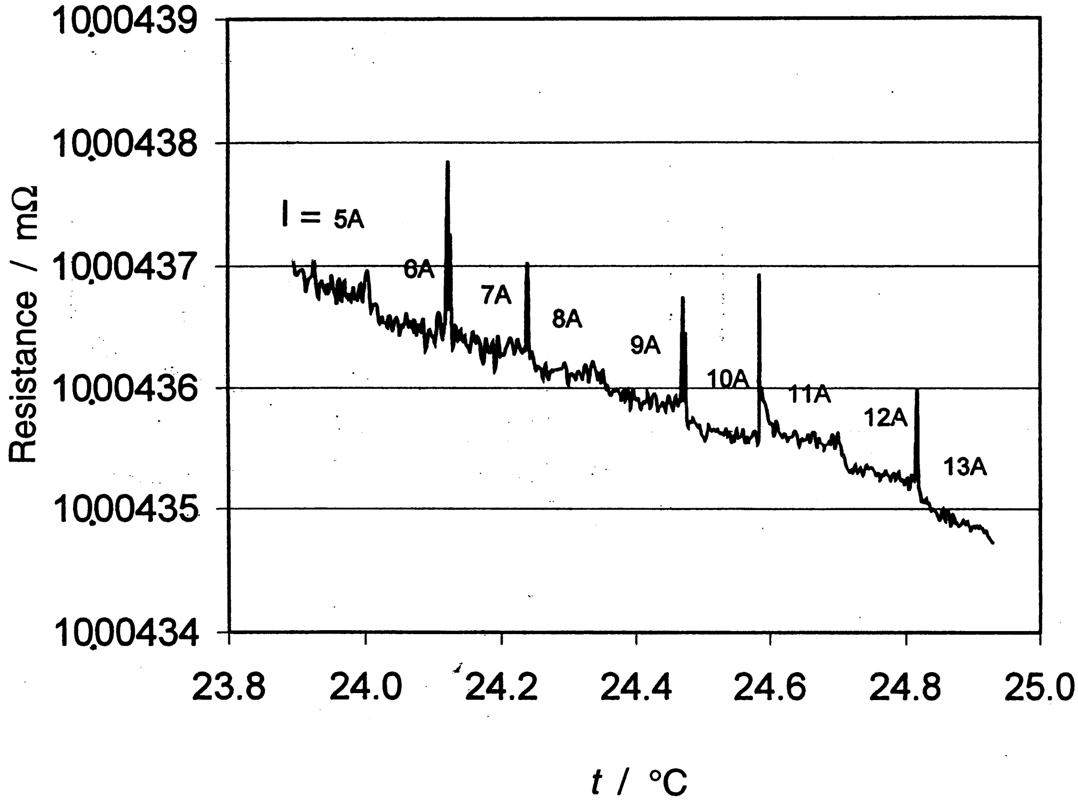
**Appendix VIb.** Non-linearity of the small aperture

| | |
|---|---|
| ○ | experimental data points for a function |
| | $F_S = 2i(\phi/2) / i(\phi)$ for $\phi >= 2\ \phi_{Cu}$ |
| | $= 1$ for $\phi = \phi_{Cu}$ |
| | $= i(2\phi) / 2i(\phi)$ for $\phi <= \phi_{Cu}/2$ where i and $\phi$ are photo current and flux, respectively |
| □ | data points from a hand-drawn curve (not shown) for $F_S$ |
| ......... | analytical expression for $F_S$ obtained by fitting a curve to the data points from the hand-drawn curve |
| ◆ | correction factor $F_{NS}$ for the non-linearity obtained by calculation based on the expression for $F_S$ |
| —— | analytical expression for $F_{NS}$ |




where $i(\phi)$ and $i(\phi_{Cu})$ are the photo currents when the pyrometer targets the lamp and the Cu blackbody, respectively

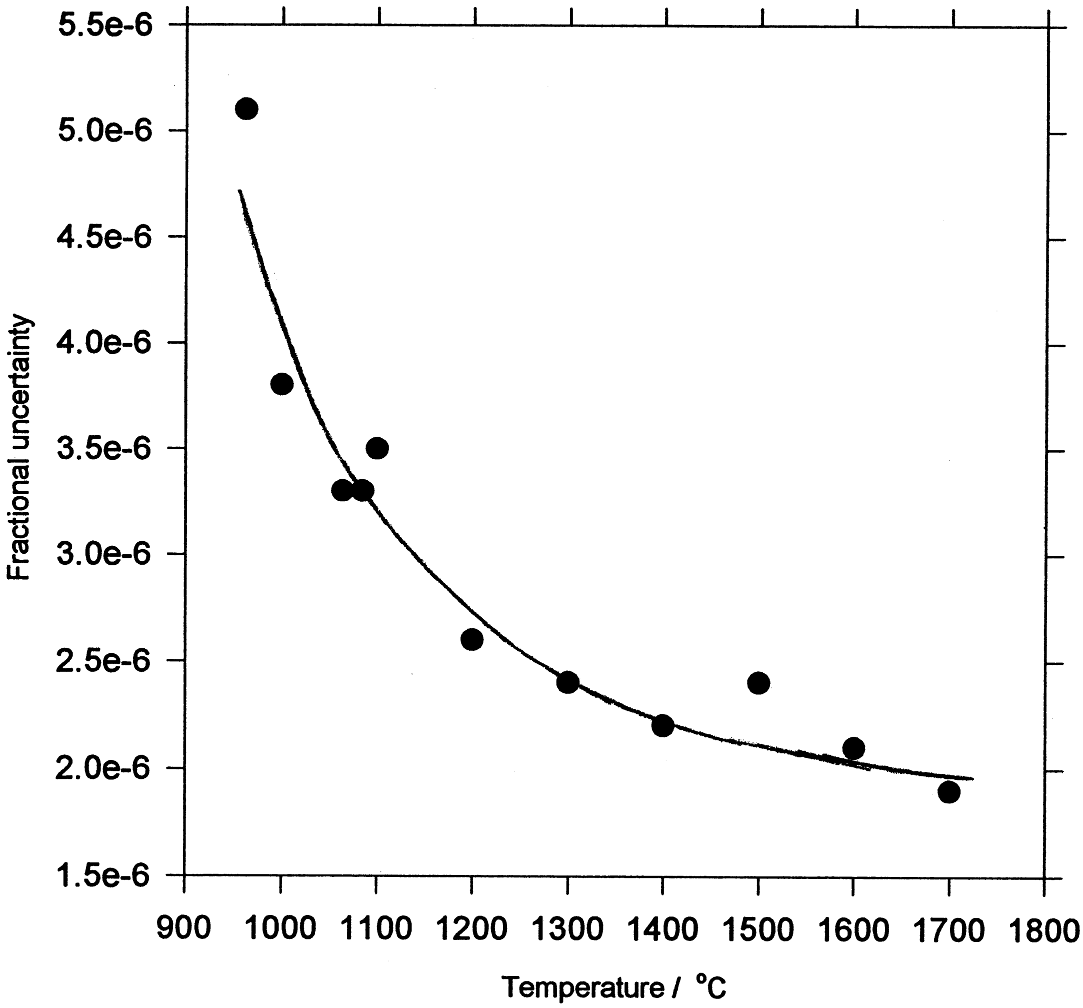
**Appendix VII**. Calibration of the standard resistor (Tinsley #1568) used for lamp current measurements.



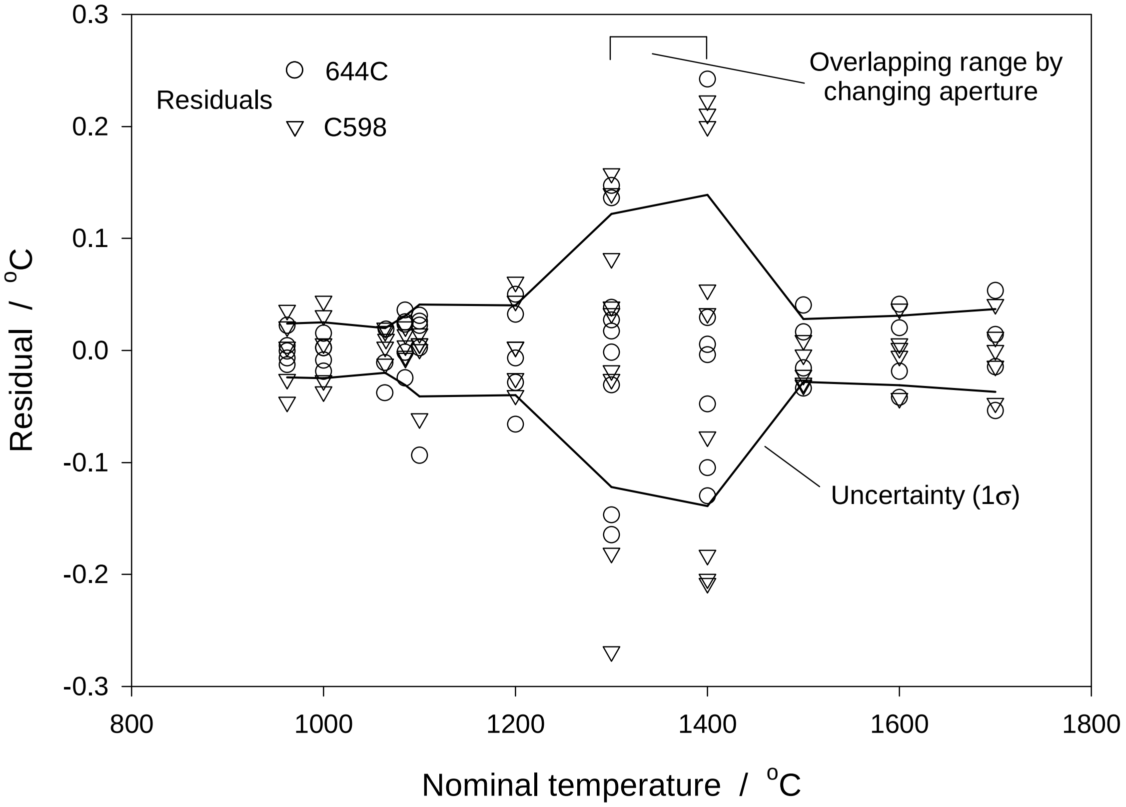

*t* : temperature of the oil bath (an integral part of the standard resistor) in which the resistive
element of the standard resistor is immersed.

I : current passing through the standard resistor in an ambient at 24 °C.

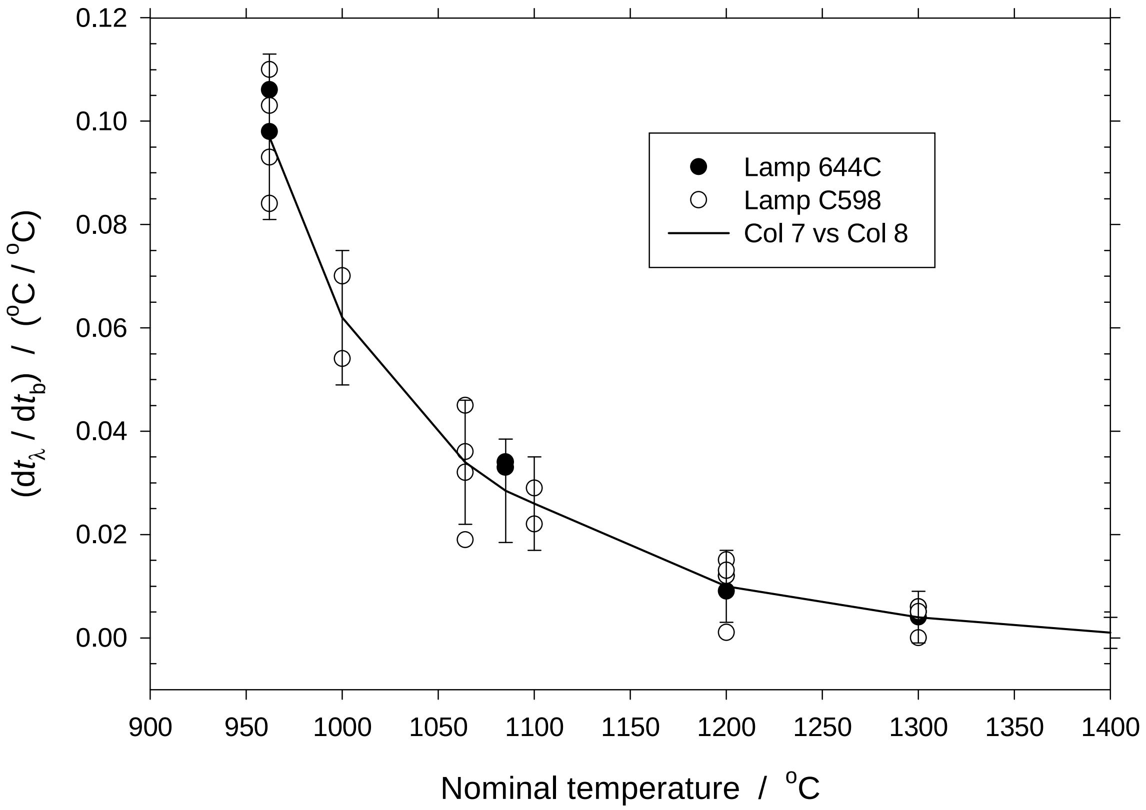
**Appendix VIII**. Fractional uncertainties in lamp current due to fluctuations in readings.



**Appendix IX.** Uncertainty (1σ) in curve fitting based on the combined residuals in Table B3 for both lamps 644C and C598



**Appendix X.** Change of the radiance temperature $t_\lambda$ with the change of the temperature of the lamp base $t_b$ (note that the curve, based on freehand drawing, is to facilitate the drawing of the estimated error bars and was not used in the calculation for the corrections in Table B2).



**Appendix XI.** NRC Data for Lamp C598

Notes:

(a) The resistance of the standard resistor used for the measurement of the lamp current is 10.004 36 mΩ.
(b) The resistance of the feedback resistor in the photoelectric detector is 1 GΩ.
(c) The *f*-number is 7.7 for the large aperture and 23.8 for the small apertures.
(d) The diameter of the circular field stop is 0.6 mm.

**Table I:** Raw data

| Index | Lamp current | | Temperature of lamp base | Large aperture | | Small aperture | |
|---|---|---|---|---|---|---|---|
| | | | | Ratio of photo currents | Temperature of lamp | Ratio of photo currents | Temperature of lamp |
| | Reference | As set | Measured | Measured | Calculated | Measured | Calculated |
| $j$ | $I_j$ | $I_\ell$ | $t_b$ | $i(t_\lambda) / i(t_{Cu})$ | $t_\lambda$ | $i(t_\lambda) / i(t_{Cu})$ | $t_\lambda$ |
| | A | A | $^oC$ | | $^oC$ | | $^oC$ |
| 1st run (May 10 - 15, 2001) | | | | | | | |
| 1 | 5.027 | 5.02518 | 19.983 | 0.197510 | 961.750 | | |
| 2 | 5.298 | 5.29583 | 19.989 | 0.335702 | 999.410 | | |
| 3 | 5.808 | 5.80513 | 19.950 | 0.775055 | 1063.720 | | |
| 4 | 5.981 | 5.97845 | 20.009 | 0.994989 | 1084.198 | | |
| 5 | 6.116 | 6.11299 | 20.009 | 1.194887 | 1099.610 | | |
| 6 | 7.054 | 7.05109 | 20.030 | 3.563738 | 1199.403 | | |
| 7 | 8.092 | 8.08833 | 20.058 | 9.250636 | 1299.174 | 9.243814 | 1299.092 |
| 8 | 9.210 | 9.20566 | 20.094 | 21.434229 | 1398.973 | 21.427640 | 1398.934 |
| 9 | 10.393 | 10.38889 | 20.133 | | | 45.203731 | 1498.847 |
| 10 | 11.635 | 11.62972 | 20.176 | | | 88.010596 | 1598.673 |
| 11 | 12.930 | 12.92436 | 20.225 | | | 160.160799 | 1698.480 |
| 2nd run (May 16 & 17, 2001) | | | | | | | |
| 1 | 5.027 | 5.02516 | 19.979 | 0.197309 | 961.680 | | |
| 2 | 5.298 | 5.29584 | 19.953 | 0.335341 | 999.331 | | |
| 3 | 5.808 | 5.80510 | 19.999 | 0.774872 | 1063.701 | | |
| 4 | 5.981 | 5.97845 | 19.962 | 0.993885 | 1084.106 | | |
| 5 | 6.116 | 6.11299 | 20.040 | 1.193939 | 1099.542 | | |
| 6 | 7.054 | 7.05107 | 20.030 | 3.560554 | 1199.315 | | |
| 7 | 8.092 | 8.08833 | 20.045 | 9.244420 | 1299.099 | 9.236691 | 1299.006 |
| 8 | 9.210 | 9.20566 | 20.061 | 21.430478 | 1398.951 | 21.424167 | 1398.914 |
| 9 | 10.393 | 10.38885 | 20.102 | | | 45.198267 | 1498.830 |
| 10 | 11.635 | 11.62972 | 20.151 | | | 88.004449 | 1598.662 |
| 11 | 12.930 | 12.92436 | 20.197 | | | 160.147530 | 1698.465 |
| 3rd run (May 18, 2001) | | | | | | | |
| 1 | 5.027 | 5.02514 | 19.938 | 0.197348 | 961.694 | | |
| 2 | 5.298 | 5.29584 | 19.944 | 0.335395 | 999.344 | | |
| 3 | 5.808 | 5.80512 | 19.959 | 0.774918 | 1063.706 | | |
| 4 | 5.981 | 5.97845 | 19.958 | 0.994099 | 1084.124 | | |
| 5 | 6.116 | 6.11299 | 19.962 | 1.193993 | 1099.546 | | |
| 6 | 7.054 | 7.05110 | 19.986 | 3.561265 | 1199.335 | | |
| 7 | 8.092 | 8.08834 | 20.022 | 9.245958 | 1299.118 | | |
| 8 | 9.210 | 9.20567 | 20.061 | 21.432604 | 1398.964 | 21.428519 | 1398.940 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | 10.393 | 10.38856 | 20.099 | | | 45.200414 | 1498.837 |
| 10 | 11.635 | 11.62972 | 20.148 | | | 88.006401 | 1598.665 |
| 11 | 12.930 | 12.92435 | 20.192 | | | 160.135821 | 1698.453 |
| 4th run (August 20, 2002)<br>(The experimental setup had been changed to run another experiment. The lamp was returned from PTB. The Cu blackbody used in previous calibrations broke. A new Cu blackbody was used.) | | | | | | | |
| 1 | 5.027 | 5.02471 | 20.153 | 0.197017 | 961.579 | | |
| 2 | 5.298 | 5.29569 | 20.166 | 0.334944 | 999.244 | | |
| 3 | 5.808 | 5.80581 | 20.207 | 0.774782 | 1063.691 | | |
| 4 | 5.981 | 5.97884 | 20.215 | 0.993344 | 1084.060 | | |
| 5 | 6.116 | 6.11352 | 20.228 | 1.193187 | 1099.489 | | |
| 6 | 7.054 | 7.05078 | 20.295 | 3.555587 | 1199.179 | 3.543435 | 1198.843 |
| 7 | 8.092 | 8.08865 | 20.365 | 9.236557 | 1299.004 | 9.206366 | 1298.639 |
| 8 | 9.210 | 9.20579 | 20.448 | 21.411246 | 1398.837 | 21.354994 | 1398.506 |
| 9 | 10.393 | 10.38857 | 20.534 | | | 45.042629 | 1498.341 |
| 10 | 11.635 | 11.62998 | 20.639 | | | 87.728535 | 1598.165 |
| 11 | 12.930 | 12.92546 | 20.730 | | | 159.705580 | 1697.980 |
| 5th run (August 26, 2002) | | | | | | | |
| 1 | 5.027 | 5.02487 | 20.305 | 0.196914 | 961.540 | | |
| 2 | 5.298 | 5.29594 | 20.320 | 0.334965 | 999.248 | | |
| 3 | 5.808 | 5.80598 | 20.336 | 0.774798 | 1063.693 | | |
| 4 | 5.981 | 5.97877 | 20.361 | 0.993050 | 1084.036 | | |
| 5 | 6.116 | 6.16367 | 20.351 | 1.274803 | 1105.143 | | |
| 6 | 7.054 | 7.05103 | 20.418 | 3.556571 | 1199.206 | | |
| 7 | 8.092 | 8.08845 | 20.489 | 9.234497 | 1298.979 | 9.203414 | 1298.603 |
| 8 | 9.210 | 9.20607 | 20.579 | 21.411788 | 1398.841 | 21.350955 | 1398.482 |
| 9 | 10.393 | 10.38854 | 20.665 | | | 45.020489 | 1498.271 |
| 10 | 11.635 | 11.62999 | 20.752 | | | 87.682702 | 1598.082 |
| 11 | 12.930 | 12.92438 | 20.886 | | | 159.545940 | 1697.805 |

**Table II:** Data after corrections for the undesirable transmission of the interference filter in the infra-red

Correction factor is expressed as $F_I = 1 - \Delta i / i$ where i is the total photo current and $\Delta i$ is that part of i due to the IR transmission.

For the Cu blackbody, correction factor $F_I(Cu) = 0.996\ 378$

For the lamp, correction factor

$$F_I(L) = 0.999\ 128\ 74 + 0.000\ 923\ 34\ u - 0.000\ 724\ 68\ u^2 + 0.000\ 827\ 08\ u^3 - 0.000\ 512\ 63\ u^4 \quad (1)$$

$$\text{where } u = (t_\lambda / °C - 1330) / 370 \quad (2)$$

| Index | Large aperture | | Small aperture | | Large aperture | Small aperture |
|---|---|---|---|---|---|---|
| | Correction factor for lamp | Ratio of photo currents | Correction factor for lamp | Ratio of photo currents | Scaled temperature | |
| j | $F_l(L)$ Using Eq. (1) | $i(t_\lambda) / i(t_{Cu})$ = $i(t_\lambda) / i(t_{Cu})$ in Table I x $F_l(L)$ / $F_l(Cu)$ | $F_l(L)$ Using Eq. (1) | $i(t_\lambda) / i(t_{Cu})$ = $i(t_\lambda) / i(t_{Cu})$ in Table I x $F_l(L)$ / $F_l(Cu)$ | u Using Eq. (2) and $t_\lambda$ in Table I | |
| 1st run | | | | | | |
| 1 | 0.99617 | 0.19747 | | | -0.99527 | |
| 2 | 0.99681 | 0.33585 | | | -0.89349 | |
| 3 | 0.99764 | 0.77604 | | | -0.71968 | |
| 4 | 0.99785 | 0.99646 | | | -0.66433 | |
| 5 | 0.99800 | 1.19683 | | | -0.62268 | |
| 6 | 0.99867 | 3.57193 | | | -0.35296 | |
| 7 | 0.99905 | 9.27541 | 0.99905 | 9.26857 | -0.08331 | -0.08354 |
| 8 | 0.99928 | 21.49667 | 0.99928 | 21.49006 | 0.18641 | 0.18631 |
| 9 | 0.99913 | | 0.99946 | 45.34335 | | 0.45634 |
| 10 | 0.99913 | | 0.99959 | 88.29442 | | 0.72614 |
| 11 | 0.99913 | | 0.99964 | 160.68550 | | 0.99589 |
| 2nd run | | | | | | |
| 1 | 0.99617 | 0.19727 | | | -0.99546 | |
| 2 | 0.99681 | 0.33549 | | | -0.89370 | |
| 3 | 0.99764 | 0.77586 | | | -0.71973 | |
| 4 | 0.99785 | 0.99536 | | | -0.66458 | |
| 5 | 0.99800 | 1.19588 | | | -0.62286 | |
| 6 | 0.99867 | 3.56874 | | | -0.35320 | |
| 7 | 0.99905 | 9.26917 | 0.99905 | 9.26142 | -0.08352 | -0.08377 |
| 8 | 0.99928 | 21.49290 | 0.99928 | 21.48657 | 0.18635 | 0.18625 |
| 9 | 0.99913 | | 0.99946 | 45.33787 | | 0.45630 |
| 10 | 0.99913 | | 0.99959 | 88.28826 | | 0.72611 |
| 11 | 0.99913 | | 0.99964 | 160.67219 | | 0.99585 |
| 3rd run | | | | | | |
| 1 | 0.99617 | 0.19731 | 0.99913 | | -0.99542 | |
| 2 | 0.99681 | 0.33554 | 0.99913 | | -0.89366 | |
| 3 | 0.99764 | 0.77590 | 0.99913 | | -0.71971 | |
| 4 | 0.99785 | 0.99557 | 0.99913 | | -0.66453 | |
| 5 | 0.99800 | 1.19593 | 0.99913 | | -0.62285 | |
| 6 | 0.99867 | 3.56945 | 0.99913 | | -0.35315 | |
| 7 | 0.99905 | 9.27072 | 0.99913 | | -0.08346 | |
| 8 | 0.99928 | 21.49504 | 0.99928 | 21.49094 | 0.18639 | 0.18632 |
| 9 | | | 0.99946 | 45.34003 | | 0.45632 |
| 10 | | | 0.99959 | 88.29021 | | 0.72612 |
| 11 | | | 0.99964 | 160.66044 | | 0.99582 |
| 4th run | | | | | | |
| 1 | 0.99617 | 0.19698 | | | -0.99573 | |
| 2 | 0.99681 | 0.33509 | | | -0.89394 | |
| 3 | 0.99764 | 0.77577 | | | -0.71975 | |
| 4 | 0.99785 | 0.99481 | | | -0.66470 | |
| 5 | 0.99800 | 1.19512 | | | -0.62300 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 6 | 0.99867 | 3.56376 | 0.99867 | 3.55157 | -0.35357 | -0.35448 |
| 7 | 0.99905 | 9.26129 | 0.99904 | 9.23101 | -0.08377 | -0.08476 |
| 8 | 0.99928 | 21.47361 | 0.99928 | 21.41718 | 0.18605 | 0.18515 |
| 9 | 0.99913 | | 0.99945 | 45.18172 | | 0.45498 |
| 10 | 0.99913 | | 0.99959 | 88.01141 | | 0.72477 |
| 11 | 0.99913 | | 0.99964 | 160.22881 | | 0.99454 |
| 5th run | | | | | | |
| 1 | 0.99617 | 0.19687 | | | -0.99584 | |
| 2 | 0.99681 | 0.33511 | | | -0.89392 | |
| 3 | 0.99764 | 0.77578 | | | -0.71975 | |
| 4 | 0.99785 | 0.99452 | | | -0.66477 | |
| 5 | 0.99804 | 1.27693 | | | -0.60772 | |
| 6 | 0.99867 | 3.56474 | | | -0.35350 | |
| 7 | 0.99905 | 9.25922 | 0.99904 | 9.22805 | -0.08384 | -0.08486 |
| 8 | 0.99928 | 21.47415 | 0.99928 | 21.41313 | 0.18606 | 0.18509 |
| 9 | 0.99913 | | 0.99945 | 45.15950 | | 0.45479 |
| 10 | 0.99913 | | 0.99959 | 87.96542 | | 0.72455 |
| 11 | 0.99913 | | 0.99964 | 160.06865 | | 0.99407 |

**Table A1**: Calibration before corrections for the size-of-source effect, non-linearity, etc.

| Index | Lamp current | | | Large aperture | | Small aperture | |
|---|---|---|---|---|---|---|---|
| | Reference | As set | Difference | Ratio of photo currents | Temperature | Ratio of photo currents | Temperature |
| $j$ | $I_j$ | $I_\ell$ | $I_j$ - $I_\ell$ | $i(t_\lambda)$ / $i(t_{Cu})$ | $t_\lambda(\lambda_e; t_b; I_\ell)$ | $i(t_\lambda)$ / $i(t_{Cu})$ | $t_\lambda(\lambda_e; t_b; I_\ell)$ |
| | From Table I | From Table I | | From Table II | By calculation | From Table II | By calculation |
| | A | A | A | | $^{o}$C | | $^{o}$C |
| 1st run | | | | | | | |
| 1 | 5.027 | 5.02518 | 0.00182 | 0.19747 | 961.736 | | |
| 2 | 5.298 | 5.29583 | 0.00217 | 0.33585 | 999.443 | | |
| 3 | 5.808 | 5.80513 | 0.00287 | 0.77604 | 1063.823 | | |
| 4 | 5.981 | 5.97845 | 0.00255 | 0.99646 | 1084.321 | | |
| 5 | 6.116 | 6.11299 | 0.00301 | 1.19683 | 1099.748 | | |
| 6 | 7.054 | 7.05109 | 0.00291 | 3.57193 | 1199.628 | | |
| 7 | 8.092 | 8.08833 | 0.00367 | 9.27541 | 1299.473 | 9.26857 | 1299.390 |
| 8 | 9.210 | 9.20566 | 0.00434 | 21.49667 | 1399.341 | 21.49006 | 1399.302 |
| 9 | 10.393 | 10.38889 | 0.00411 | | | 45.34335 | 1499.285 |
| 10 | 11.635 | 11.62972 | 0.00528 | | | 88.29442 | 1599.182 |
| 11 | 12.930 | 12.92436 | 0.00564 | | | 160.68550 | 1699.054 |
| 2nd run | | | | | | | |
| 1 | 5.027 | 5.02516 | 0.00184 | 0.19727 | 961.666 | | |
| 2 | 5.298 | 5.29584 | 0.00216 | 0.33549 | 999.364 | | |
| 3 | 5.808 | 5.80510 | 0.00290 | 0.77586 | 1063.804 | | |
| 4 | 5.981 | 5.97845 | 0.00255 | 0.99536 | 1084.229 | | |
| 5 | 6.116 | 6.11299 | 0.00301 | 1.19588 | 1099.680 | | |
| 6 | 7.054 | 7.05107 | 0.00293 | 3.56874 | 1199.540 | | |
| 7 | 8.092 | 8.08833 | 0.00367 | 9.26917 | 1299.398 | 9.26142 | 1299.304 |
| 8 | 9.210 | 9.20566 | 0.00434 | 21.49290 | 1399.319 | 21.48657 | 1399.281 |
| 9 | 10.393 | 10.38885 | 0.00415 | | | 45.33787 | 1499.267 |
| 10 | 11.635 | 11.62972 | 0.00528 | | | 88.28826 | 1599.171 |
| 11 | 12.930 | 12.92436 | 0.00564 | | | 160.67219 | 1699.040 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3rd run | | | | | | | |
| 1 | 5.027 | 5.02514 | 0.00186 | 0.19731 | 961.680 | | |
| 2 | 5.298 | 5.29584 | 0.00216 | 0.33554 | 999.375 | | |
| 3 | 5.808 | 5.80512 | 0.00288 | 0.77590 | 1063.808 | | |
| 4 | 5.981 | 5.97845 | 0.00255 | 0.99557 | 1084.247 | | |
| 5 | 6.116 | 6.11299 | 0.00301 | 1.19593 | 1099.684 | | |
| 6 | 7.054 | 7.05110 | 0.00290 | 3.56945 | 1199.560 | | |
| 7 | 8.092 | 8.08834 | 0.00366 | 9.27072 | 1299.416 | | |
| 8 | 9.210 | 9.20567 | 0.00433 | 21.49504 | 1399.331 | 21.49094 | 1399.307 |
| 9 | 10.393 | 10.38856 | 0.00444 | | | 45.34003 | 1499.274 |
| 10 | 11.635 | 11.62972 | 0.00528 | | | 88.29021 | 1599.175 |
| 11 | 12.930 | 12.92435 | 0.00565 | | | 160.66044 | 1699.027 |
| 4th run | | | | | | | |
| 1 | 5.027 | 5.02471 | 0.00229 | 0.19698 | 961.565 | | |
| 2 | 5.298 | 5.29569 | 0.00231 | 0.33509 | 999.277 | | |
| 3 | 5.808 | 5.80581 | 0.00219 | 0.77577 | 1063.794 | | |
| 4 | 5.981 | 5.97884 | 0.00216 | 0.99481 | 1084.183 | | |
| 5 | 6.116 | 6.11352 | 0.00248 | 1.19512 | 1099.626 | | |
| 6 | 7.054 | 7.05078 | 0.00322 | 3.56376 | 1199.404 | 3.55157 | 1199.068 |
| 7 | 8.092 | 8.08865 | 0.00335 | 9.26129 | 1299.303 | 9.23101 | 1298.937 |
| 8 | 9.210 | 9.20579 | 0.00421 | 21.47361 | 1399.205 | 21.41718 | 1398.873 |
| 9 | 10.393 | 10.38857 | 0.00443 | | | 45.18172 | 1498.778 |
| 10 | 11.635 | 11.62998 | 0.00502 | | | 88.01141 | 1598.674 |
| 11 | 12.930 | 12.92546 | 0.00454 | | | 160.22881 | 1698.554 |
| 5th run | | | | | | | |
| 1 | 5.027 | 5.02487 | 0.00213 | 0.19687 | 961.526 | | |
| 2 | 5.298 | 5.29594 | 0.00206 | 0.33511 | 999.281 | | |
| 3 | 5.808 | 5.80598 | 0.00202 | 0.77578 | 1063.795 | | |
| 4 | 5.981 | 5.97877 | 0.00223 | 0.99452 | 1084.159 | | |
| 5 | 6.116 | 6.16367 | -0.04767 | 1.27693 | 1105.286 | | |
| 6 | 7.054 | 7.05103 | 0.00297 | 3.56474 | 1199.431 | | |
| 7 | 8.092 | 8.08845 | 0.00355 | 9.25922 | 1299.278 | 9.22805 | 1298.901 |
| 8 | 9.210 | 9.20607 | 0.00393 | 21.47415 | 1399.208 | 21.41313 | 1398.849 |
| 9 | 10.393 | 10.38854 | 0.00446 | | | 45.15950 | 1498.708 |
| 10 | 11.635 | 11.62999 | 0.00501 | | | 87.96542 | 1598.591 |
| 11 | 12.930 | 12.92438 | 0.00562 | | | 160.06865 | 1698.379 |

**Table A2:** Calibration after corrections for the size-of-source effect

Correction factor is expressed as $F_S = 1 - \Delta i / i$ where i is the total photo current and $\Delta i$ is that part of i due to the out-of-field radiation.

*For the large aperture*: $\Delta i / i$ is equal to 0.0015 for the lamp and 0.0058 for the Cu blackbody.

Correction factor for the ratio of photo currents $i(t_\lambda) / i(t_{Cu})$ is equal to

$$F_{SL} = 1 - 0.0015 + 0.0058 = 1.0043.$$

*For the small aperture*: $\Delta i / i$ is equal to 0.0039 for the lamp and 0.0118 for the Cu blackbody.

Correction factor for the ratio of photo currents $i(t_\lambda) / i(t_{Cu})$ is equal to

$$F_{SS} = 1 - 0.0039 + 0.0118 = 1.0079.$$

| Index | Large aperture | | Small aperture | |
|---|---|---|---|---|
| | Ratio of photo currents | Temperature | Ratio of photo currents | Temperature |
| j | $i(t_\lambda) / i(t_{Cu})$ = | $t_\lambda(\lambda_e; t_b; I_\ell)$ | $i(t_\lambda) / i(t_{Cu})$ = | $t_\lambda(\lambda_e; t_b; I_\ell)$ |
| | $F_{SL}$ x $i(t_\lambda) / i(t_{Cu})$ in Table A1 | $^oC$ | $F_{SS}$ x $i(t_\lambda) / i(t_{Cu})$ in Table A1 | $^oC$ |
| 1st run | | | | |
| 1 | 0.19832 | 962.032 | | |
| 2 | 0.33729 | 999.756 | | |
| 3 | 0.77938 | 1064.169 | | |
| 4 | 1.00075 | 1084.679 | | |
| 5 | 1.20197 | 1100.113 | | |
| 6 | 3.58729 | 1200.049 | | |
| 7 | 9.31529 | 1299.952 | 9.34179 | 1300.270 |
| 8 | 21.58910 | 1399.883 | 21.65983 | 1400.297 |
| 9 | | | 45.70157 | 1500.402 |
| 10 | | | 88.99195 | 1600.429 |
| 11 | | | 161.95492 | 1700.438 |
| 2nd run | | | | |
| 1 | 0.19812 | 961.962 | | |
| 2 | 0.33693 | 999.677 | | |
| 3 | 0.77919 | 1064.150 | | |
| 4 | 0.99964 | 1084.587 | | |
| 5 | 1.20102 | 1100.046 | | |
| 6 | 3.58408 | 1199.961 | | |
| 7 | 9.30903 | 1299.877 | 9.33459 | 1300.184 |
| 8 | 21.58532 | 1399.861 | 21.65632 | 1400.276 |
| 9 | | | 45.69604 | 1500.385 |
| 10 | | | 88.98573 | 1600.418 |
| 11 | | | 161.94150 | 1700.423 |
| 3rd run | | | | |
| 1 | 0.19816 | 961.976 | | |
| 2 | 0.33698 | 999.688 | | |
| 3 | 0.77924 | 1064.155 | | |
| 4 | 0.99985 | 1084.604 | | |
| 5 | 1.20107 | 1100.049 | | |
| 6 | 3.58480 | 1199.980 | | |
| 7 | 9.31058 | 1299.896 | | |
| 8 | 21.58746 | 1399.873 | 21.66072 | 1400.302 |
| 9 | | | 45.69821 | 1500.392 |
| 10 | | | 88.98771 | 1600.422 |
| 11 | | | 161.92966 | 1700.410 |
| 4th run | | | | |
| 1 | 0.19782 | 961.858 | | |
| 2 | 0.33653 | 999.591 | | |
| 3 | 0.77910 | 1064.140 | | |
| 4 | 0.99909 | 1084.541 | | |
| 5 | 1.20026 | 1099.992 | | |
| 6 | 3.57908 | 1199.824 | 3.57963 | 1199.839 |
| 7 | 9.30111 | 1299.782 | 9.30393 | 1299.816 |
| 8 | 21.56595 | 1399.747 | 21.58638 | 1399.867 |

| | | | | |
|---|---|---|---|---|
| 9 | | | 45.53865 | 1499.895 |
| 10 | | | 88.70670 | 1599.920 |
| 11 | | | 161.49461 | 1699.937 |
| 5th run | | | | |
| 1 | 0.19772 | 961.823 | | |
| 2 | 0.33655 | 999.595 | | |
| 3 | 0.77912 | 1064.142 | | |
| 4 | 0.99880 | 1084.517 | | |
| 5 | 1.28243 | 1105.656 | | |
| 6 | 3.58007 | 1199.851 | | |
| 7 | 9.29904 | 1299.757 | 9.30095 | 1299.780 |
| 8 | 21.56649 | 1399.751 | 21.58229 | 1399.843 |
| 9 | | | 45.51626 | 1499.825 |
| 10 | | | 88.66034 | 1599.837 |
| 11 | | | 161.33319 | 1699.761 |

**Table A3:** Calibration after corrections for non-linearity

Correction factor for the ratio of the photo currents $i(t_\lambda) / i(t_{Cu})$ is expressed as $F_N = 1 - \Delta i / i$ where i is the total photo current and $\Delta i$ is that part of i due to the non-linearity.

For the large aperture, the correction factor is given by

$F_{NL} = 1 + (v - v^*)(0.000\ 018\ 97 + 0.001\ 355\ 17\ v + 0.001\ 005\ 17\ v^2 + 0.000\ 225\ 52\ v^3)$
(3)

For the small aperture, the correction factor is given by

$F_{NS} = 1 + (v - v^*)(0.000\ 003\ 08 + 0.000\ 121\ 36\ v + 0.000\ 190\ 44\ v^2 + 0.000\ 073\ 09\ v^3)$
(4)

where $v = \{\ln[i(t_\lambda) / i(t_{Cu})] - 3\} / 2.3$ (5)

and $v^* = -3 / 2.3$

| Index | Large aperture | | | | Small aperture | | | | Large aperture | Small aperture |
|---|---|---|---|---|---|---|---|---|---|---|
| | Correction factor | Ratio of photo currents | Effective wavelength | Temperature | Correction factor | Ratio of photo currents | Effective wavelength | Temperature | Scaled photo current ratio | |
| j | $F_{NL}$ | $i(t_\lambda) / i(t_{Cu})$ = | $\lambda_e$ | $t_\lambda(\lambda_e; t_b; I_\ell)$ | $F_{NS}$ | $i(t_\lambda) / i(t_{Cu})$ = | $\lambda_e$ | $t_\lambda(\lambda_e; t_b; I_\ell)$ | v | |
| | Using Eq. (3) | $F_{NL}$ x $i(t_\lambda) / i(t_{Cu})$ in Table A2 | nm | $^oC$ | Using Eq. (4) | $F_{NS}$ x $i(t_\lambda) / i(t_{Cu})$ in Table A2 | nm | $^oC$ | Using Eq. (5) and $i(t_\lambda) / i(t_{Cu})$ in Table A2 | |
| 1st run | | | | | | | | | | |
| 1 | 1.00033 | 0.19838 | 650.034 | 962.053 | | | | | -2.00777 | |
| 2 | 1.00023 | 0.33737 | 650.028 | 999.773 | | | | | -1.77687 | |
| 3 | 1.00006 | 0.77942 | 650.019 | 1064.174 | | | | | -1.41272 | |
| 4 | 1.00000 | 1.00075 | 650.016 | 1084.679 | | | | | -1.30402 | |
| 5 | 0.99996 | 1.20192 | 650.014 | 1100.109 | | | | | -1.22436 | |
| 6 | 0.99971 | 3.58624 | 650.002 | 1200.020 | | | | | -0.74896 | |
| 7 | 0.99968 | 9.31231 | 649.991 | 1299.917 | 0.99998 | 9.34162 | 649.991 | 1300.268 | -0.33406 | -0.33283 |
| 8 | 1.00008 | 21.59090 | 649.982 | 1399.894 | 1.00001 | 21.66004 | 649.982 | 1400.298 | 0.03139 | 0.03281 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 9 | | | | | 1.00012 | 45.70720 | 649.973 | 1500.419 | | 0.35745 |
| 10 | | | | | 1.00035 | 89.02342 | 649.966 | 1600.485 | | 0.64719 |
| 11 | | | | | 1.00072 | 162.07123 | 649.959 | 1700.564 | | 0.90753 |
| 2nd run | | | | | | | | | | |
| 1 | 1.00033 | 0.19818 | 650.034 | 961.983 | | | | | -2.00822 | |
| 2 | 1.00023 | 0.33700 | 650.028 | 999.693 | | | | | -1.77734 | |
| 3 | 1.00006 | 0.77924 | 650.019 | 1064.155 | | | | | -1.41283 | |
| 4 | 1.00000 | 0.99964 | 650.016 | 1084.587 | | | | | -1.30451 | |
| 5 | 0.99996 | 1.20097 | 650.014 | 1100.042 | | | | | -1.22471 | |
| 6 | 0.99971 | 3.58303 | 650.002 | 1199.932 | | | | | -0.74935 | |
| 7 | 0.99968 | 9.30605 | 649.991 | 1299.841 | 0.99998 | 9.33442 | 649.991 | 1300.182 | -0.33435 | -0.33316 |
| 8 | 1.00008 | 21.58712 | 649.982 | 1399.871 | 1.00001 | 21.65653 | 649.982 | 1400.277 | 0.03131 | 0.03274 |
| 9 | | | | | 1.00012 | 45.70167 | 649.973 | 1500.402 | | 0.35740 |
| 10 | | | | | 1.00035 | 89.01720 | 649.966 | 1600.474 | | 0.64716 |
| 11 | | | | | 1.00072 | 162.05779 | 649.959 | 1700.550 | | 0.90749 |
| 3rd run | | | | | | | | | | |
| 1 | 1.00033 | 0.19822 | 650.034 | 961.997 | | | | | -2.00813 | |
| 2 | 1.00023 | 0.33706 | 650.028 | 999.706 | | | | | -1.77727 | |
| 3 | 1.00006 | 0.77928 | 650.019 | 1064.159 | | | | | -1.41280 | |
| 4 | 1.00000 | 0.99985 | 650.016 | 1084.604 | | | | | -1.30441 | |
| 5 | 0.99996 | 1.20102 | 650.014 | 1100.046 | | | | | -1.22469 | |
| 6 | 0.99971 | 3.58375 | 650.002 | 1199.952 | | | | | -0.74926 | |
| 7 | 0.99968 | 9.30760 | 649.991 | 1299.860 | | | | | -0.33428 | |
| 8 | 1.00008 | 21.58927 | 649.982 | 1399.884 | 1.00001 | 21.66093 | 649.982 | 1400.303 | 0.03135 | 0.03283 |
| 9 | | | | | 1.00012 | 45.70384 | 649.973 | 1500.409 | | 0.35742 |
| 10 | | | | | 1.00035 | 89.01917 | 649.966 | 1600.478 | | 0.64717 |
| 11 | | | | | 1.00072 | 162.04593 | 649.959 | 1700.537 | | 0.90746 |
| 4th run | | | | | | | | | | |
| 1 | 1.00033 | 0.19789 | 650.034 | 961.882 | | | | | -2.00886 | |
| 2 | 1.00023 | 0.33661 | 650.028 | 999.608 | | | | | -1.77786 | |
| 3 | 1.00006 | 0.77915 | 650.019 | 1064.146 | | | | | -1.41288 | |
| 4 | 1.00000 | 0.99909 | 650.016 | 1084.541 | | | | | -1.30474 | |
| 5 | 0.99996 | 1.20021 | 650.014 | 1099.988 | | | | | -1.22498 | |
| 6 | 0.99971 | 3.57803 | 650.002 | 1199.795 | 0.99999 | 3.57960 | 650.002 | 1199.838 | -0.74995 | -0.74989 |
| 7 | 0.99968 | 9.29813 | 649.991 | 1299.746 | 0.99998 | 9.30376 | 649.991 | 1299.814 | -0.33472 | -0.33459 |
| 8 | 1.00008 | 21.56773 | 649.982 | 1399.758 | 1.00001 | 21.58658 | 649.982 | 1399.868 | 0.03092 | 0.03133 |
| 9 | | | | | 1.00012 | 45.54422 | 649.973 | 1499.912 | | 0.35590 |
| 10 | | | | | 1.00035 | 88.73793 | 649.966 | 1599.976 | | 0.64580 |
| 11 | | | | | 1.00072 | 161.61025 | 649.959 | 1700.063 | | 0.90629 |
| 5th run | | | | | | | | | | |
| 1 | 1.00033 | 0.19779 | 650.034 | 961.847 | | | | | -2.00909 | |
| 2 | 1.00023 | 0.33663 | 650.028 | 999.612 | | | | | -1.77783 | |
| 3 | 1.00006 | 0.77916 | 650.019 | 1064.147 | | | | | -1.41287 | |
| 4 | 1.00000 | 0.99880 | 650.016 | 1084.517 | | | | | -1.30487 | |
| 5 | 0.99994 | 1.28235 | 650.013 | 1105.65 | | | | | -1.19619 | |
| 6 | 0.99971 | 3.57902 | 650.002 | 1199.822 | | | | | -0.74983 | |
| 7 | 0.99968 | 9.29606 | 649.991 | 1299.721 | 0.99998 | 9.30078 | 649.991 | 1299.778 | -0.33482 | -0.33473 |
| 8 | 1.00008 | 21.56827 | 649.982 | 1399.761 | 1.00001 | 21.58250 | 649.982 | 1399.844 | 0.03093 | 0.03125 |
| 9 | | | | | 1.00012 | 45.52183 | 649.973 | 1499.842 | | 0.35568 |
| 10 | | | | | 1.00035 | 88.69154 | 649.966 | 1599.893 | | 0.64557 |
| 11 | | | | | 1.00072 | 161.44859 | 649.959 | 1699.887 | | 0.90586 |

**Table B1:** Calibration after corrections for wavelength

From "Protocol" by P. Bloembergen:

$$\partial t_\lambda / \partial \lambda \ / \ (°C / nm) = -\,0.35422504 \times 10^{-1} + 2.70716088 \times 10^{-5}\, t_\lambda / °C - 0.10980270 \times 10^{-6}\, (t_\lambda / °C)^2 \qquad (6)$$

Reference wavelength $\lambda_r$ = 650 nm

| Index j | Large aperture | | | | Small aperture | | | |
|---|---|---|---|---|---|---|---|---|
| | Sensitivity | Wavelength difference | Wavelength correction | Temperature | Sensitivity | Wavelength difference | Wavelength correction | Temperature |
| | $\partial t_\lambda / \partial \lambda$ | $\Delta\lambda$ = | $\Delta t$ = | $t_\lambda(\lambda_r; t_b; I_\ell)$ = | $\partial t_\lambda / \partial \lambda$ | $\Delta\lambda$ = | $\Delta t$ = | $t_\lambda(\lambda_r; t_b; I_\ell)$ = |
| | Using Eq. (6) and $t_\lambda$ in Table A3 | $\lambda_r - \lambda_e$ in Table A3 | $\partial t_\lambda / \partial \lambda \times \Delta\lambda$ | $t_\lambda(\lambda_e; t_b; I_\ell)$ in Table A3 + $\Delta t$ | Using Eq. (6) and $t_\lambda$ in Table A3 | $\lambda_r - \lambda_e$ in Table A3 | $\partial t_\lambda / \partial \lambda \times \Delta\lambda$ | $t_\lambda(\lambda_e; t_b; I_\ell)$ in Table A3 + $\Delta t$ |
| | °C / nm | nm | °C | °C | °C / nm | nm | °C | °C |
| 1st run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 962.057 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.776 | | | | |
| 3 | -0.131 | -0.019 | 0.002 | 1064.176 | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.681 | | | | |
| 5 | -0.139 | -0.014 | 0.002 | 1100.111 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1200.020 | | | | |
| 7 | -0.186 | 0.009 | -0.002 | 1299.915 | -0.186 | 0.009 | -0.002 | 1300.266 |
| 8 | -0.213 | 0.018 | -0.004 | 1399.890 | -0.213 | 0.018 | -0.004 | 1400.294 |
| 9 | | | | | -0.242 | 0.027 | -0.007 | 1500.412 |
| 10 | | | | | -0.273 | 0.034 | -0.009 | 1600.476 |
| 11 | | | | | -0.307 | 0.041 | -0.013 | 1700.551 |
| 2nd run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 961.987 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.696 | | | | |
| 3 | -0.131 | -0.019 | 0.002 | 1064.157 | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.589 | | | | |
| 5 | -0.139 | -0.014 | 0.002 | 1100.044 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1199.932 | | | | |
| 7 | -0.186 | 0.009 | -0.002 | 1299.839 | -0.186 | 0.009 | -0.002 | 1300.180 |
| 8 | -0.213 | 0.018 | -0.004 | 1399.867 | -0.213 | 0.018 | -0.004 | 1400.273 |
| 9 | | | | | -0.242 | 0.027 | -0.007 | 1500.395 |
| 10 | | | | | -0.273 | 0.034 | -0.009 | 1600.465 |
| 11 | | | | | -0.307 | 0.041 | -0.013 | 1700.537 |
| 3rd run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 962.001 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.709 | | | | |
| 3 | -0.131 | -0.019 | 0.002 | 1064.161 | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.606 | | | | |
| 5 | -0.139 | -0.014 | 0.002 | 1100.048 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1199.952 | | | | |
| 7 | -0.186 | 0.009 | -0.002 | 1299.858 | | | | |
| 8 | -0.213 | 0.018 | -0.004 | 1399.880 | -0.213 | 0.018 | -0.004 | 1400.299 |
| 9 | | | | | -0.242 | 0.027 | -0.007 | 1500.402 |
| 10 | | | | | -0.273 | 0.034 | -0.009 | 1600.469 |
| 11 | | | | | -0.307 | 0.041 | -0.013 | 1700.524 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 4th run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 961.886 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.611 | | | | |
| 3 | -0.131 | -0.019 | 0.002 | 1064.148 | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.543 | | | | |
| 5 | -0.139 | -0.014 | 0.002 | 1099.990 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1199.795 | -0.161 | -0.002 | 0.000 | 1199.838 |
| 7 | -0.186 | 0.009 | -0.002 | 1299.744 | -0.186 | 0.009 | -0.002 | 1299.812 |
| 8 | -0.213 | 0.018 | -0.004 | 1399.754 | -0.213 | 0.018 | -0.004 | 1399.864 |
| 9 | | | | | -0.242 | 0.027 | -0.007 | 1499.905 |
| 10 | | | | | -0.273 | 0.034 | -0.009 | 1599.967 |
| 11 | | | | | -0.307 | 0.041 | -0.013 | 1700.050 |
| 5th run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 961.851 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.615 | | | | |
| 3 | -0.131 | -0.019 | 0.002 | 1064.149 | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.519 | | | | |
| 5 | -0.140 | -0.013 | 0.002 | 1105.652 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1199.822 | | | | |
| 7 | -0.186 | 0.009 | -0.002 | 1299.719 | -0.186 | 0.009 | -0.002 | 1299.776 |
| 8 | -0.213 | 0.018 | -0.004 | 1399.757 | -0.213 | 0.018 | -0.004 | 1399.840 |
| 9 | | | | | -0.242 | 0.027 | -0.007 | 1499.835 |
| 10 | | | | | -0.273 | 0.034 | -0.009 | 1599.884 |
| 11 | | | | | -0.307 | 0.041 | -0.013 | 1699.874 |

**Table B2:** Calibration after corrections for the temperatures of the lamp base

Reference temperature for the lamp base  $t_r$ = 20°C

For 961.78°C ≤ $t_\lambda$ ≤ 1100°C,  $\partial t_\lambda / \partial t_b = 0.0175 - 0.0274\, w + 0.0382\, w^2 - 0.0250\, w^3$ (7)

where  $w = (t_\lambda / °C - 1125) / 175$ (8)

For  $t_\lambda$ ~ 1200°C,  $\partial t_\lambda / \partial t_b = 0.010$
For  $t_\lambda$ ~ 1300°C,  $\partial t_\lambda / \partial t_b = 0.003$
For  $t_\lambda$ ~ 1400°C and higher,  $\partial t_\lambda / \partial t_b = 0.000$

| Index | Current | Large aperture | | | | Small aperture | | | | Large aperture | Small aperture |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sensitivity | Base temperature difference | Base temperature correction | Temperature | Sensitivity | Base temperature difference | Base temperature correction | Temperature | Scaled Temperature | |
| j | $I_\ell$ | $\partial t_\lambda / \partial t_b$ | $\Delta t_b =$ | $\Delta t =$ | $t_\lambda(\lambda_r;\, t_r;\, I_\ell) =$ | $\partial t_\lambda / \partial t_b$ | $\Delta t_b =$ | $\Delta t =$ | $t_\lambda(\lambda_r;\, t_r;\, I_\ell) =$ | w | |
| | From Table I | Using Eq. (7) or assigned values given above | $t_r - t_b$ in Table I | $\partial t_\lambda / \partial t_b \times \Delta t_b$ | $t_\lambda(\lambda_r;\, t_b;\, I_\ell)$ in Table B1 + $\Delta t$ | Using assigned values given above | $t_r - t_b$ in Table I | $\partial t_\lambda / \partial t_b \times \Delta t_b$ | $t_\lambda(\lambda_r;\, t_b;\, I_\ell)$ in Table B1 + $\Delta t$ | Using Eq. (8) and $t_\lambda$ in Table B1 | |
| | A | | °C | °C | °C | | °C | °C | °C | | |
| 1st run | | | | | | | | | | | |
| 1 | 5.02518 | 0.096 | 0.017 | 0.002 | 962.058 | | | | | -0.93110 | |
| 2 | 5.29583 | 0.066 | 0.011 | 0.001 | 999.777 | | | | | -0.71556 | |
| 3 | 5.80513 | 0.033 | 0.050 | 0.002 | 1064.178 | | | | | -0.34756 | |
| 4 | 5.97845 | 0.026 | -0.009 | 0.000 | 1084.681 | | | | | -0.23039 | |
| 5 | 6.11299 | 0.022 | -0.009 | 0.000 | 1100.111 | | | | | -0.14222 | |
| 6 | 7.05109 | 0.010 | -0.030 | 0.000 | 1200.020 | | | | | 0.42869 | |
| 7 | 8.08833 | 0.003 | -0.058 | 0.000 | 1299.915 | 0.003 | -0.058 | 0.000 | 1300.266 | 0.99952 | 1.00152 |
| 8 | 9.20566 | 0.000 | -0.094 | 0.000 | 1399.890 | 0.000 | -0.094 | 0.000 | 1400.294 | 1.57080 | 1.57311 |
| 9 | 10.38889 | | | | | 0.000 | -0.133 | 0.000 | 1500.412 | | 2.14521 |
| 10 | 11.62972 | | | | | 0.000 | -0.176 | 0.000 | 1600.476 | | 2.71700 |
| 11 | 12.92436 | | | | | 0.000 | -0.225 | 0.000 | 1700.551 | | 3.28887 |
| 2nd run | | | | | | | | | | | |
| 1 | 5.02516 | 0.096 | 0.021 | 0.002 | 961.989 | | | | | -0.93150 | |
| 2 | 5.29584 | 0.066 | 0.047 | 0.003 | 999.699 | | | | | -0.71602 | |
| 3 | 5.80510 | 0.033 | 0.001 | 0.000 | 1064.158 | | | | | -0.34767 | |
| 4 | 5.97845 | 0.026 | 0.038 | 0.001 | 1084.590 | | | | | -0.23092 | |
| 5 | 6.11299 | 0.022 | -0.040 | -0.001 | 1100.043 | | | | | -0.14261 | |
| 6 | 7.05107 | 0.010 | -0.030 | 0.000 | 1199.932 | | | | | 0.42818 | |
| 7 | 8.08833 | 0.003 | -0.045 | 0.000 | 1299.839 | 0.030 | -0.045 | -0.001 | 1300.179 | 0.99908 | 1.00103 |
| 8 | 9.20566 | 0.000 | -0.061 | 0.000 | 1399.867 | 0.000 | -0.061 | 0.000 | 1400.273 | 1.57067 | 1.57299 |
| 9 | 10.38885 | | | | | 0.000 | -0.102 | 0.000 | 1500.395 | | 2.14512 |
| 10 | 11.62972 | | | | | 0.000 | -0.151 | 0.000 | 1600.465 | | 2.71694 |
| 11 | 12.92436 | | | | | 0.000 | -0.197 | 0.000 | 1700.537 | | 3.28879 |
| 3rd run | | | | | | | | | | | |
| 1 | 5.02514 | 0.096 | 0.062 | 0.006 | 962.007 | | | | | -0.93142 | |
| 2 | 5.29584 | 0.066 | 0.056 | 0.004 | 999.713 | | | | | -0.71595 | |
| 3 | 5.80512 | 0.033 | 0.041 | 0.001 | 1064.163 | | | | | -0.34765 | |
| 4 | 5.97845 | 0.026 | 0.042 | 0.001 | 1084.607 | | | | | -0.23082 | |
| 5 | 6.11299 | 0.022 | 0.038 | 0.001 | 1100.049 | | | | | -0.14258 | |
| 6 | 7.05110 | 0.010 | 0.014 | 0.000 | 1199.952 | | | | | 0.42830 | |
| 7 | 8.08834 | 0.003 | -0.022 | 0.000 | 1299.858 | | | | | 0.99919 | |
| 8 | 9.20567 | 0.000 | -0.061 | 0.000 | 1399.880 | 0.000 | -0.061 | 0.000 | 1400.299 | 1.57074 | 1.57314 |
| 9 | 10.38856 | | | | | 0.000 | -0.099 | 0.000 | 1500.402 | | 2.14516 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 11.62972 | | | | | 0.000 | -0.148 | 0.000 | 1600.469 | | 2.71696 |
| 11 | 12.92435 | | | | | 0.000 | -0.192 | 0.000 | 1700.524 | | 3.28871 |
| 4th run | | | | | | | | | | | |
| 1 | 5.02471 | 0.096 | -0.153 | -0.015 | 961.871 | | | | | -0.93208 | |
| 2 | 5.29569 | 0.066 | -0.166 | -0.011 | 999.600 | | | | | -0.71651 | |
| 3 | 5.80581 | 0.033 | -0.207 | -0.007 | 1064.142 | | | | | -0.34772 | |
| 4 | 5.97884 | 0.026 | -0.215 | -0.006 | 1084.538 | | | | | -0.23118 | |
| 5 | 6.11352 | 0.022 | -0.228 | -0.005 | 1099.985 | | | | | -0.14291 | |
| 6 | 7.05078 | 0.010 | -0.295 | -0.003 | 1199.792 | 0.010 | -0.295 | -0.003 | 1199.835 | 0.42740 | 0.42765 |
| 7 | 8.08865 | 0.003 | -0.365 | -0.001 | 1299.743 | 0.030 | -0.365 | -0.011 | 1299.801 | 0.99854 | 0.99893 |
| 8 | 9.20579 | 0.000 | -0.448 | 0.000 | 1399.754 | 0.000 | -0.448 | 0.000 | 1399.864 | 1.57002 | 1.57065 |
| 9 | 10.38857 | | | | | 0.000 | -0.534 | 0.000 | 1499.905 | | 2.14232 |
| 10 | 11.62998 | | | | | 0.000 | -0.639 | 0.000 | 1599.967 | | 2.71410 |
| 11 | 12.92546 | | | | | 0.000 | -0.730 | 0.000 | 1700.050 | | 3.28600 |
| 5th run | | | | | | | | | | | |
| 1 | 5.02487 | 0.097 | -0.305 | -0.029 | 961.821 | | | | | -0.93228 | |
| 2 | 5.29594 | 0.066 | -0.320 | -0.021 | 999.594 | | | | | -0.71648 | |
| 3 | 5.80598 | 0.033 | -0.336 | -0.011 | 1064.139 | | | | | -0.34772 | |
| 4 | 5.97877 | 0.026 | -0.361 | -0.009 | 1084.510 | | | | | -0.23132 | |
| 5 | 6.16367 | 0.021 | -0.351 | -0.007 | 1105.644 | | | | | -0.11056 | |
| 6 | 7.05103 | 0.010 | -0.418 | -0.004 | 1199.818 | | | | | 0.42756 | |
| 7 | 8.08845 | 0.003 | -0.489 | -0.001 | 1299.718 | 0.003 | -0.489 | -0.001 | 1299.775 | 0.99840 | 0.99872 |
| 8 | 9.20607 | 0.000 | -0.579 | 0.000 | 1399.757 | 0.000 | -0.579 | 0.000 | 1399.840 | 1.57004 | 1.57052 |
| 9 | 10.38854 | | | | | 0.000 | -0.665 | 0.000 | 1499.835 | | 2.14192 |
| 10 | 11.62999 | | | | | 0.000 | -0.752 | 0.000 | 1599.884 | | 2.71362 |
| 11 | 12.92438 | | | | | 0.000 | -0.886 | 0.000 | 1699.874 | | 3.28500 |

**Table B3**: Calibration in terms of radiance temperature as a function of lamp current at the reference wavelength and lamp-base temperature

A polynomial is fitted to the data of $t_\lambda$ and $I_\lambda$ for the 1st, 2nd and 3rd runs in Table B2 (data before the departure of the lamp to PTB) to express $t_\lambda$ as a function of $I_\lambda$.

Another polynomial is fitted to the data for the 4th and 5th runs (data after the return of the lamp from PTB).

For the 1st, 2nd and 3rd runs,

$$t_\lambda \,/\, °C = 1382.1188 + 351.2963\, z - 35.0628\, z^2 + 17.2444\, z^3 - 11.3464\, z^4 - 3.5995\, z^5 - 3.3128\, z^6 + 9.1076\, z^7 \quad (9)$$

For the 4th and 5th runs,

$$t_\lambda \,/\, °C = 1381.8217 + 351.0045\, z - 35.8689\, z^2 + 15.7387\, z^3 - 9.0408\, z^4 + 0.9508\, z^5 - 4.9093\, z^6 + 6.0380\, z^7 \quad (10)$$

$$\text{where } z = (l_\lambda / A - 9) / 4 \qquad (11)$$

$$\text{and } 961.78 \leq t_\lambda / °C \leq 1700$$

| Index | Current | | | Large aperture | | Small aperture | |
|---|---|---|---|---|---|---|---|
| | As set | Scaled | Temperature | Temperature | Residual | Temperature | Residual |
| | | | Computed | Measured | Computed - Measured | Measured | Computed - Measured |
| j | $I_\ell$ | z | $t_\lambda(\lambda_r; t_r; I_\ell)$ | $t_\lambda(\lambda_r; t_r; I_\ell)$ | $\Delta t_\lambda$ | $t_\lambda(\lambda_r; t_r; I_\ell)$ | $\Delta t_\lambda$ |
| | From Table B2 | Using Eq. (11) | Using Eq. (9) or (10) | From Table B2 | | From Table B2 | |
| | A | | °C | °C | °C | °C | °C |
| 1st run | | | | | | | |
| 1 | 5.02518 | -0.993705 | 962.011 | 962.058 | -0.047 | | |
| 2 | 5.29583 | -0.926043 | 999.740 | 999.777 | -0.037 | | |
| 3 | 5.80513 | -0.798718 | 1064.181 | 1064.178 | 0.003 | | |
| 4 | 5.97845 | -0.755388 | 1084.611 | 1084.681 | -0.070 | | |
| 5 | 6.11299 | -0.721753 | 1100.050 | 1100.111 | -0.061 | | |
| 6 | 7.05109 | -0.487228 | 1199.995 | 1200.020 | -0.025 | | |
| 7 | 8.08833 | -0.227918 | 1299.998 | 1299.915 | 0.082 | 1300.266 | -0.269 |
| 8 | 9.20566 | 0.051415 | 1400.090 | 1399.890 | 0.200 | 1400.294 | -0.204 |
| 9 | 10.38889 | 0.347223 | 1500.408 | | | 1500.412 | -0.004 |
| 10 | 11.62972 | 0.657430 | 1600.471 | | | 1600.476 | -0.005 |
| 11 | 12.92436 | 0.981090 | 1700.537 | | | 1700.551 | -0.014 |
| 2nd run | | | | | | | |
| 1 | 5.02516 | -0.993710 | 962.008 | 961.989 | 0.020 | | |
| 2 | 5.29584 | -0.926040 | 999.741 | 999.699 | 0.042 | | |
| 3 | 5.8051 | -0.798725 | 1064.177 | 1064.158 | 0.020 | | |
| 4 | 5.97845 | -0.755388 | 1084.611 | 1084.590 | 0.021 | | |
| 5 | 6.11299 | -0.721753 | 1100.050 | 1100.043 | 0.007 | | |
| 6 | 7.05107 | -0.487233 | 1199.993 | 1199.932 | 0.061 | | |
| 7 | 8.08833 | -0.227918 | 1299.998 | 1299.839 | 0.158 | 1300.179 | -0.181 |
| 8 | 9.20566 | 0.051415 | 1400.090 | 1399.867 | 0.223 | 1400.273 | -0.183 |
| 9 | 10.38885 | 0.347213 | 1500.405 | | | 1500.395 | 0.009 |
| 10 | 11.62972 | 0.657430 | 1600.471 | | | 1600.465 | 0.006 |
| 11 | 12.92436 | 0.981090 | 1700.537 | | | 1700.537 | 0.000 |
| 3rd run | | | | | | | |
| 1 | 5.02514 | -0.993715 | 962.005 | 962.007 | -0.001 | | |
| 2 | 5.29584 | -0.926040 | 999.741 | 999.713 | 0.028 | | |
| 3 | 5.80512 | -0.798720 | 1064.180 | 1064.163 | 0.017 | | |
| 4 | 5.97845 | -0.755388 | 1084.611 | 1084.607 | 0.004 | | |
| 5 | 6.11299 | -0.721753 | 1100.050 | 1100.049 | 0.001 | | |
| 6 | 7.0511 | -0.487225 | 1199.996 | 1199.952 | 0.044 | | |
| 7 | 8.08834 | -0.227915 | 1299.998 | 1299.858 | 0.140 | | |
| 8 | 9.20567 | 0.051417 | 1400.091 | 1399.880 | 0.211 | 1400.299 | -0.208 |
| 9 | 10.38856 | 0.347140 | 1500.381 | | | 1500.402 | -0.022 |
| 10 | 11.62972 | 0.657430 | 1600.471 | | | 1600.469 | 0.002 |
| 11 | 12.92435 | 0.981088 | 1700.537 | | | 1700.524 | 0.012 |
| 4th run | | | | | | | |
| 1 | 5.02471 | -0.993823 | 961.857 | 961.871 | -0.014 | | |
| 2 | 5.29569 | -0.926078 | 999.581 | 999.600 | -0.019 | | |
| 3 | 5.80581 | -0.798548 | 1064.132 | 1064.142 | -0.009 | | |
| 4 | 5.97884 | -0.755290 | 1084.535 | 1084.538 | -0.003 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5 | 6.11352 | -0.721620 | 1099.991 | 1099.985 | 0.007 | | |
| 6 | 7.05078 | -0.487305 | 1199.795 | 1199.792 | 0.003 | 1199.835 | -0.040 |
| 7 | 8.08865 | -0.227838 | 1299.776 | 1299.743 | 0.033 | 1299.801 | -0.026 |
| 8 | 9.20579 | 0.051448 | 1399.787 | 1399.754 | 0.033 | 1399.864 | -0.077 |
| 9 | 10.38857 | 0.347143 | 1499.875 | | | 1499.905 | -0.031 |
| 10 | 11.62998 | 0.657495 | 1599.924 | | | 1599.967 | -0.043 |
| 11 | 12.92546 | 0.981365 | 1700.004 | | | 1700.050 | -0.047 |
| 5th run | | | | | | | |
| 1 | 5.02487 | -0.993783 | 961.880 | 961.821 | 0.058 | | |
| 2 | 5.29594 | -0.926015 | 999.615 | 999.594 | 0.021 | | |
| 3 | 5.80598 | -0.798505 | 1064.153 | 1064.139 | 0.014 | | |
| 4 | 5.97877 | -0.755308 | 1084.526 | 1084.510 | 0.017 | | |
| 5 | 6.16367 | -0.709083 | 1105.660 | 1105.644 | 0.016 | | |
| 6 | 7.05103 | -0.487243 | 1199.821 | 1199.818 | 0.003 | | |
| 7 | 8.08845 | -0.227888 | 1299.757 | 1299.718 | 0.039 | 1299.775 | -0.018 |
| 8 | 9.20607 | 0.051518 | 1399.811 | 1399.757 | 0.054 | 1399.840 | -0.029 |
| 9 | 10.38854 | 0.347135 | 1499.872 | | | 1499.835 | 0.037 |
| 10 | 11.62999 | 0.657498 | 1599.925 | | | 1599.884 | 0.041 |
| 11 | 12.92438 | 0.981095 | 1699.921 | | | 1699.874 | 0.046 |

The deviation of Eq. (10) from Eq. (9) is taken to be the change of the calibration after the return of the lamp from PTB:

$$\Delta t_\lambda \,/\, °C = -0.2910 - 0.2918\,z - 0.8061\,z^2 - 1.5057\,z^3 + 2.3056\,z^4 + 4.5503\,z^5 - 1.6065\,z6 - 3.0696\,z^7 \qquad (12)$$

The changes at the reference lamp currents are given in the following table:

| Index | Lamp current | | Nominal temperature | Temperature change |
|---|---|---|---|---|
| | Absolute | Scaled | | |
| j | $I_\ell$ | z | $t_\lambda$ | $\Delta t_\lambda$ |
| | From Table A1 | Using Eq. (11) | | Using Eq. (12) |
| | A | | °C | °C |
| | | | | |
| 1 | 5.027 | -0.99325 | 961.780 | -0.091 |
| 2 | 5.298 | -0.92550 | 1000.000 | -0.140 |
| 3 | 5.808 | -0.79800 | 1064.180 | -0.126 |
| 4 | 5.981 | -0.75475 | 1084.620 | -0.118 |
| 5 | 6.116 | -0.72100 | 1100.000 | -0.114 |
| 6 | 7.054 | -0.48650 | 1200.000 | -0.163 |
| 7 | 8.092 | -0.22700 | 1300.000 | -0.245 |
| 8 | 9.210 | 0.05250 | 1400.000 | -0.309 |
| 9 | 10.393 | 0.34825 | 1500.000 | -0.502 |
| 10 | 11.635 | 0.65875 | 1600.000 | -0.561 |
| 11 | 12.930 | 0.98250 | 1700.000 | -0.627 |

The mean of Eqs. (9) and (10) is taken to be the analytical representation of the calibration of the lamp:

$$t_\lambda \,/\, °C = 1381.9703 + 351.1504\, z - 35.4659\, z^2 + 16.4916\, z^3 - 10.1936\, z^4 - 1.3244\, z^5 - 4.1111\, z^6 + 7.5728\, z^7 \tag{13}$$

where z is a (non-dimensionalized) lamp current after scaling according to Eq. (11).

To facilitate comparison at the reference currents the following table is given:

| Index | Lamp current | | Temperature |
|---|---|---|---|
| | Absolute | Scaled | |
| j | $I_\ell$ | z | $t_\lambda(\lambda_r; t_r; I_\ell)$ |
| | From Table A1 | Using Eq. (11) | Using Eq. (13) |
| | A | | °C |
| | | | |
| 1 | 5.027 | -0.99325 | 962.231 |
| 2 | 5.298 | -0.92550 | 999.961 |
| 3 | 5.808 | -0.79800 | 1064.460 |
| 4 | 5.981 | -0.75475 | 1084.846 |
| 5 | 6.116 | -0.72100 | 1100.332 |
| 6 | 7.054 | -0.48650 | 1200.204 |
| 7 | 8.092 | -0.22700 | 1300.212 |
| 8 | 9.210 | 0.05250 | 1400.310 |
| 9 | 10.393 | 0.34825 | 1500.494 |
| 10 | 11.635 | 0.65875 | 1600.602 |
| 11 | 12.930 | 0.98250 | 1700.664 |

**Appendix XII.** NRC Data for Lamp 644C

Notes:

(e) The resistance of the standard resistor used for the measurement of the lamp current is 10.004 36 mΩ.
(f) The resistance of the feedback resistor in the photoelectric detector is 1 GΩ.
(g) The *f*-number is 7.7 for the large aperture and 23.8 for the small apertures.
(h) The diameter of the circular field stop is 0.6 mm.

**Table I:** Raw data

| | | | | Large aperture | | Small aperture | |
|---|---|---|---|---|---|---|---|
| Index | Lamp current | | Temperature of lamp base | Ratio of photo currents | Temperature of lamp | Ratio of photo currents | Temperature of lamp |
| j | Reference $I_j$ (A) | As set $I_\ell$ (A) | Measured $t_b$ ($^oC$) | Measured $i(t_\lambda) / i(t_{Cu})$ | Calculated $t_\lambda$ ($^oC$) | Measured $i(t_\lambda) / i(t_{Cu})$ | Calculated $t_\lambda$ ($^oC$) |
| 1st run (April 27, 2001) | | | | | | | |
| 1 | 5.185 | 5.18290 | 19.989 | 0.1973386 | 961.690 | | |
| 2 | 5.457 | 5.45445 | 19.989 | 0.3361236 | 999.501 | | |
| 3 | 5.966 | | | | | | |
| 4 | 6.141 | 6.13825 | 19.981 | 0.9952613 | 1084.221 | | |
| 5 | 6.276 | 6.27330 | 20.005 | 1.1950503 | 1099.621 | | |
| 6 | 7.223 | 7.21982 | 20.020 | 3.5635511 | 1199.398 | | |
| 7 | 8.276 | 8.27214 | 20.081 | 9.2531384 | 1299.204 | 9.2415697 | 1299.065 |
| 8 | 9.411 | 9.40735 | 20.110 | | | 21.4151901 | 1398.861 |
| 9 | 10.617 | 10.61192 | 20.165 | | | 45.1840215 | 1498.785 |
| 10 | 11.880 | 11.87454 | 20.218 | | | 87.9683475 | 1598.597 |
| 11 | 13.197 | 13.19122 | 20.264 | | | 160.1096714 | 1698.424 |
| 2nd run (April 30, 2001)<br>(This run followed the last run. Lamp alignment was the same as previously.) | | | | | | | |
| 1 | 5.185 | 5.18286 | 20.015 | 0.1972960 | 961.676 | | |
| 2 | 5.457 | 5.45445 | 20.015 | 0.3360727 | 999.490 | | |
| 3 | 5.966 | | | | | | |
| 4 | 6.141 | 6.13826 | 20.035 | 0.9951636 | 1084.213 | | |
| 5 | 6.276 | 6.27331 | 20.043 | 1.1950035 | 1099.618 | | |
| 6 | 7.223 | 7.21980 | 20.074 | 3.5641497 | 1199.414 | | |
| 7 | 8.276 | 8.27214 | 20.128 | 9.2540279 | 1299.215 | 9.2430919 | 1299.093 |
| 8 | 9.411 | 9.40733 | 20.143 | 21.4313921 | 1398.956 | 21.4193857 | 1398.886 |
| 9 | 10.617 | 10.61192 | 20.187 | | | 45.1929982 | 1498.813 |
| 10 | 11.880 | 11.87447 | 20.225 | | | 87.9864960 | 1598.629 |
| 11 | 13.197 | 13.19120 | 20.274 | | | 160.1350402 | 1698.452 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3rd run (June 13, 2001)<br>(This run required re-installation and re-alignment of the lamp.) | | | | | | | |
| 1 | 5.185 | 5.18290 | 19.981 | 0.1973729 | 961.701 | | |
| 2 | 5.457 | 5.45448 | 19.989 | 0.3361911 | 999.517 | | |
| 3 | 5.966 | 5.96316 | 20.000 | 0.7750488 | 1063.719 | | |
| 4 | 6.141 | 6.13828 | 20.033 | 0.9959180 | 1084.276 | | |
| 5 | 6.276 | 6.27332 | 19.966 | 1.1967556 | 1099.743 | | |
| 6 | 7.223 | 7.21981 | 20.004 | 3.5677350 | 1199.513 | | |
| 7 | 8.276 | 8.27215 | 20.102 | 9.2640188 | 1299.336 | | |
| 8 | 9.411 | | | | | | |
| 9 | 10.617 | | | | | | |
| 10 | 11.880 | | | | | | |
| 11 | 13.197 | | | | | | |
| 4th run (August 19, 2002)<br>(The experimental setup had been changed to run another experiment. The lamp was returned from PTB. The Cu blackbody used in the previous calibration broke. A new Cu blackbody was used.) | | | | | | | |
| 1 | 5.185 | 5.18288 | 20.200 | 0.1969698 | 961.561 | | |
| 2 | 5.457 | 5.45477 | 20.212 | 0.3358148 | 999.434 | | |
| 3 | 5.966 | 5.96350 | 20.254 | 0.7747073 | 1063.684 | | |
| 4 | 6.141 | 6.13856 | 20.259 | 0.9945663 | 1084.163 | | |
| 5 | 6.276 | 6.27343 | 20.269 | 1.1940057 | 1099.547 | | |
| 6 | 7.223 | 7.21982 | 20.323 | 3.5615770 | 1199.344 | | |
| 7 | 8.276 | 8.27204 | 20.417 | 9.2481901 | 1299.145 | 9.2115127 | 1298.701 |
| 8 | 9.411 | 9.40688 | 20.508 | 21.4180242 | 1398.878 | 21.3471286 | 1398.459 |
| 9 | 10.617 | 10.61270 | 20.606 | | | 45.0797227 | 1498.458 |
| 10 | 11.880 | 11.87282 | 20.724 | | | 87.7599969 | 1598.221 |
| 11 | 13.197 | 13.19125 | 20.842 | | | 159.6735352 | 1697.945 |
| 5th run (August 28, 2002)<br>(This run required re-installation and re-alignment of the lamp.) | | | | | | | |
| 1 | 5.185 | 5.18277 | 20.256 | 0.1968415 | 961.516 | | |
| 2 | 5.457 | 5.45466 | 20.310 | 0.3356844 | 999.405 | | |
| 3 | 5.966 | 5.96342 | 20.336 | 0.7741033 | 1063.620 | | |
| 4 | 6.141 | 6.13839 | 20.374 | 0.9946697 | 1084.172 | | |
| 5 | 6.276 | 6.27326 | 20.387 | 1.1940657 | 1099.551 | | |
| 6 | 7.223 | 7.21971 | 20.428 | 3.5620051 | 1199.356 | | |
| 7 | 8.276 | 8.27245 | 20.512 | 9.2534377 | 1299.208 | 9.2199413 | 1298.803 |
| 8 | 9.411 | 9.40690 | 20.601 | 21.4237186 | 1398.911 | 21.3563535 | 1398.514 |
| 9 | 10.617 | 10.61236 | 20.690 | | | 45.0946767 | 1498.505 |
| 10 | 11.880 | 11.87486 | 20.791 | | | 87.8013633 | 1598.296 |
| 11 | 13.197 | 13.19128 | 20.870 | | | 159.7725816 | 1698.054 |

**Table II:** Data after corrections for the undesirable transmission of the interference filter in the infra-red

Correction factor is expressed as $F_I = 1 - \Delta i / i$ where i is the total photo current and $\Delta i$ is that part of i due to the IR transmission.

For the blackbody, correction factor $F_I(Cu) = 0.996\,378$

For the lamp, correction factor

$$F_I(L) = 0.999\,128\,74 + 0.000\,923\,34\,u - 0.000\,724\,68\,u^2 + 0.000\,827\,08\,u^3 - 0.000\,512\,63\,u^4 \quad (1)$$

$$\text{where } u = (t_\lambda / {}^\circ C - 1330) / 370 \quad (2)$$

| Index | Large aperture | | Small aperture | | Large aperture | Small aperture |
|---|---|---|---|---|---|---|
| | Correction factor for lamp | Ratio of photo currents | Correction factor for lamp | Ratio of photo currents | Scaled temperature | |
| j | $F_I(L)$ | $i(t_\lambda) / i(t_{Cu})$ = | $F_I(L)$ | $i(t_\lambda) / i(t_{Cu})$ = | u | |
| | Using Eq. (1) | $i(t_\lambda) / i(t_{Cu})$ in Table I x $F_I(L)$ / $F_I(Cu)$ | Using Eq. (1) | $i(t_\lambda) / i(t_{Cu})$ in Table I x $F_I(L)$ / $F_I(Cu)$ | Using Eq. (2) and $t_\lambda$ in Table I | |
| 1st run | | | | | | |
| 1 | 0.99617 | 0.19730 | | | -0.99543 | |
| 2 | 0.99681 | 0.33627 | | | -0.89324 | |
| 3 | | | | | | |
| 4 | 0.99785 | 0.99674 | | | -0.66427 | |
| 5 | 0.99800 | 1.19699 | | | -0.62265 | |
| 6 | 0.99867 | 3.57174 | | | -0.35298 | |
| 7 | 0.99905 | 9.27792 | 0.99905 | 9.26632 | -0.08323 | -0.08361 |
| 8 | | | 0.99928 | 21.47757 | | 0.18611 |
| 9 | | | 0.99946 | 45.32358 | | 0.45618 |
| 10 | | | 0.99959 | 88.25203 | | 0.72594 |
| 11 | | | 0.99964 | 160.63421 | | 0.99574 |
| 2nd run | | | | | | |
| 1 | 0.99617 | 0.19726 | | | -0.99547 | |
| 2 | 0.99681 | 0.33622 | | | -0.89327 | |
| 3 | | | | | | |
| 4 | 0.99785 | 0.99664 | | | -0.66429 | |
| 5 | 0.99800 | 1.19694 | | | -0.62265 | |
| 6 | 0.99867 | 3.57234 | | | -0.35294 | |
| 7 | 0.99905 | 9.27881 | 0.99905 | 9.26784 | -0.08320 | -0.08353 |
| 8 | 0.99928 | 21.49382 | 0.99928 | 21.48178 | 0.18637 | 0.18618 |
| 9 | | | 0.99946 | 45.33259 | | 0.45625 |
| 10 | | | 0.99959 | 88.27024 | | 0.72602 |
| 11 | | | 0.99964 | 160.65966 | | 0.99582 |
| 3rd run | | | | | | |
| 1 | 0.99617 | 0.19733 | | | -0.99540 | |
| 2 | 0.99681 | 0.33634 | | | -0.89320 | |
| 3 | 0.99764 | 0.77603 | | | -0.71968 | |
| 4 | 0.99785 | 0.99739 | | | -0.66412 | |
| 5 | 0.99800 | 1.19870 | | | -0.62232 | |
| 6 | 0.99867 | 3.57594 | | | -0.35267 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | 0.99905 | 9.28883 | | | -0.08288 | |
| 8 | | | | | | |
| 9 | | | | | | |
| 10 | | | | | | |
| 11 | | | | | | |
| 4th run | | | | | | |
| 1 | 0.99617 | 0.19693 | | | -0.99578 | |
| 2 | 0.99681 | 0.33596 | | | -0.89342 | |
| 3 | 0.99764 | 0.77569 | | | -0.71977 | |
| 4 | 0.99785 | 0.99604 | | | -0.66442 | |
| 5 | 0.99800 | 1.19594 | | | -0.62285 | |
| 6 | 0.99867 | 3.56976 | | | -0.35312 | |
| 7 | 0.99905 | 9.27296 | 0.99904 | 9.23617 | -0.08339 | -0.08459 |
| 8 | 0.99928 | 21.48041 | 0.99928 | 21.40929 | 0.18616 | 0.18502 |
| 9 | | | 0.99945 | 45.21893 | | 0.45529 |
| 10 | | | 0.99959 | 88.04297 | | 0.72492 |
| 11 | | | 0.99964 | 160.19666 | | 0.99445 |
| 5th run | | | | | | |
| 1 | 0.99617 | 0.19680 | | | -0.99590 | |
| 2 | 0.99681 | 0.33583 | | | -0.89350 | |
| 3 | 0.99764 | 0.77509 | | | -0.71995 | |
| 4 | 0.99785 | 0.99614 | | | -0.66440 | |
| 5 | 0.99800 | 1.19600 | | | -0.62284 | |
| 6 | 0.99867 | 3.57019 | | | -0.35309 | |
| 7 | 0.99905 | 9.27822 | 0.99905 | 9.24462 | -0.08322 | -0.08432 |
| 8 | 0.99928 | 21.48612 | 0.99928 | 21.41854 | 0.18625 | 0.18517 |
| 9 | | | 0.99946 | 45.23394 | | 0.45542 |
| 10 | | | 0.99959 | 88.08448 | | 0.72512 |
| 11 | | | 0.99964 | 160.29603 | | 0.99474 |

**Table A1:** Calibration before corrections for the size-of-source effect, non-linearity, etc

| | | | | Large aperture | | Small aperture | |
|---|---|---|---|---|---|---|---|
| | Lamp current | | | Ratio of photo currents | Temperature | Ratio of photo currents | Temperature |
| Index | Reference | As set | Difference | Measured | Calculated | Measured | Calculated |
| j | $I_j$ | $I_\ell$ | $I_j - I_\ell$ | $i(t_\lambda) / i(t_{Cu})$ | $t_\lambda(\lambda_e; t_b; I_\ell)$ | $i(t_\lambda) / i(t_{Cu})$ | $t_\lambda(\lambda_e; t_b; I_\ell)$ |
| | A | A | A | From Table II | $^oC$ | From Table II | $^oC$ |
| 1st run | | | | | | | |
| 1 | 5.185 | 5.18290 | 0.00210 | 0.19730 | 961.676 | | |
| 2 | 5.457 | 5.45445 | 0.00255 | 0.33627 | 999.534 | | |
| 3 | 5.966 | | | | | | |
| 4 | 6.141 | 6.13825 | 0.00275 | 0.99674 | 1084.344 | | |
| 5 | 6.276 | 6.27330 | 0.00270 | 1.19699 | 1099.759 | | |
| 6 | 7.223 | 7.21982 | 0.00318 | 3.57174 | 1199.623 | | |
| 7 | 8.276 | 8.27214 | 0.00386 | 9.27792 | 1299.503 | 9.26632 | 1299.363 |
| 8 | 9.411 | 9.40735 | 0.00365 | | | 21.47757 | 1399.228 |
| 9 | 10.617 | 10.61192 | 0.00508 | | | 45.32358 | 1499.223 |
| 10 | 11.880 | 11.87454 | 0.00546 | | | 88.25203 | 1599.106 |
| 11 | 13.197 | 13.19122 | 0.00578 | | | 160.63421 | 1698.998 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| 2nd run | | | | | | | |
| 1 | 5.185 | 5.18286 | 0.00214 | 0.19726 | 961.663 | | |
| 2 | 5.457 | 5.45445 | 0.00255 | 0.33622 | 999.523 | | |
| 3 | 5.966 | | | | | | |
| 4 | 6.141 | 6.13826 | 0.00274 | 0.99664 | 1084.336 | | |
| 5 | 6.276 | 6.27331 | 0.00269 | 1.19694 | 1099.756 | | |
| 6 | 7.223 | 7.21980 | 0.00320 | 3.57234 | 1199.639 | | |
| 7 | 8.276 | 8.27214 | 0.00386 | 9.27881 | 1299.514 | 9.26784 | 1299.382 |
| 8 | 9.411 | 9.40735 | 0.00365 | 21.49382 | 1399.324 | 21.48178 | 1399.253 |
| 9 | 10.617 | 10.61192 | 0.00508 | | | 45.33259 | 1499.026 |
| 10 | 11.880 | 11.87447 | 0.00553 | | | 88.27024 | 1599.139 |
| 11 | 13.197 | 13.19120 | 0.00580 | | | 160.65966 | 1699.026 |
| | | | | | | | |
| 3rd run | | | | | | | |
| 1 | 5.185 | 5.18290 | 0.00210 | 0.19733 | 961.687 | | |
| 2 | 5.457 | 5.45448 | 0.00252 | 0.33634 | 999.549 | | |
| 3 | 5.966 | 5.96316 | 0.00284 | 0.77603 | 1063.821 | | |
| 4 | 6.141 | 6.13828 | 0.00272 | 0.99739 | 1084.399 | | |
| 5 | 6.276 | 6.27332 | 0.00268 | 1.19870 | 1099.881 | | |
| 6 | 7.223 | 7.21981 | 0.00319 | 3.57594 | 1199.738 | | |
| 7 | 8.276 | 8.27215 | 0.00385 | 9.28883 | 1299.634 | | |
| 8 | 9.411 | | | | | | |
| 9 | 10.617 | | | | | | |
| 10 | 11.880 | | | | | | |
| 11 | 13.197 | | | | | | |
| | | | | | | | |
| 4th run (Lamp was returned from PTB.) | | | | | | | |
| 1 | 5.185 | 5.18288 | 0.00212 | 0.19693 | 961.547 | | |
| 2 | 5.457 | 5.45477 | 0.00223 | 0.33596 | 999.466 | | |
| 3 | 5.966 | 5.96350 | 0.00250 | 0.77569 | 1063.786 | | |
| 4 | 6.141 | 6.13856 | 0.00244 | 0.99604 | 1084.286 | | |
| 5 | 6.276 | 6.27343 | 0.00257 | 1.19594 | 1099.685 | | |
| 6 | 7.223 | 7.21982 | 0.00318 | 3.56976 | 1199.568 | | |
| 7 | 8.276 | 8.27204 | 0.00396 | 9.27296 | 1299.443 | 9.23617 | 1298.999 |
| 8 | 9.411 | 9.40688 | 0.00412 | 21.48041 | 1399.245 | 21.40929 | 1398.826 |
| 9 | 10.617 | 10.61270 | 0.00430 | | | 45.21893 | 1498.895 |
| 10 | 11.880 | 11.87282 | 0.00718 | | | 88.04297 | 1598.731 |
| 11 | 13.197 | 13.19125 | 0.00575 | | | 160.19666 | 1698.519 |
| | | | | | | | |
| 5th run | | | | | | | |
| 1 | 5.185 | 5.18277 | 0.00223 | 0.19680 | 961.502 | | |
| 2 | 5.457 | 5.45466 | 0.00234 | 0.33583 | 999.438 | | |
| 3 | 5.966 | 5.96342 | 0.00258 | 0.77509 | 1063.724 | | |
| 4 | 6.141 | 6.13839 | 0.00261 | 0.99614 | 1084.295 | | |
| 5 | 6.276 | 6.27326 | 0.00274 | 1.19600 | 1099.689 | | |
| 6 | 7.223 | 7.21971 | 0.00329 | 3.57019 | 1199.580 | | |
| 7 | 8.276 | 8.27241 | 0.00359 | 9.27822 | 1299.507 | 9.24462 | 1299.102 |
| 8 | 9.411 | 9.40690 | 0.00410 | 21.48612 | 1399.279 | 21.41854 | 1398.881 |
| 9 | 10.617 | 10.61236 | 0.00464 | | | 45.23394 | 1498.942 |
| 10 | 11.880 | 11.87486 | 0.00514 | | | 88.08448 | 1598.805 |
| 11 | 13.197 | 13.19128 | 0.00572 | | | 160.29603 | 1698.628 |

**Table A2:** Calibration after corrections for the size-of-source effect

Correction factor is expressed as $F_S = 1 - \Delta i / i$ where i is the total photo current and $\Delta i$ is that part of i due to the out-of-field radiation.

For the large aperture: $\Delta i / i$ is equal to 0.0015 for the lamp and 0.0058 for the blackbody.

The correction factor for the ratio of photo currents $i(t_\lambda) / i(t_{Cu})$ is equal to $F_{SL} = 1 - 0.0015 + 0.0058 = 1.0043$.

For the small aperture: $\Delta i / i$ is equal to 0.0039 for the lamp and 0.0118 for the blackbody.

The correction factor for the ratio of photo currents $i(t_\lambda) / i(t_{Cu})$ is equal to $F_{SS} = 1 - 0.0039 + 0.0118 = 1.0079$.

| Index j | Large aperture: Ratio of photo currents $i(t_\lambda) / i(t_{Cu}) = F_{SL}$ x $i(t_\lambda) / i(t_{Cu})$ in Table A1 | Large aperture: Temperature $t_\lambda(\lambda_e; t_b; I_\ell)$ °C | Small aperture: Ratio of photo currents $i(t_\lambda) / i(t_{Cu}) = F_{SS}$ x $i(t_\lambda) / i(t_{Cu})$ in Table A1 | Small aperture: Temperature $t_\lambda(\lambda_e; t_b; I_\ell)$ °C |
|---|---|---|---|---|
| 1st run | | | | |
| 1 | 0.19815 | 961.973 | | |
| 2 | 0.33772 | 999.849 | | |
| 3 | | | | |
| 4 | 1.00102 | 1084.701 | | |
| 5 | 1.20214 | 1100.125 | | |
| 6 | 3.58710 | 1200.043 | | |
| 7 | 9.31781 | 1299.983 | 9.33952 | 1300.243 |
| 8 | | | 21.64724 | 1400.223 |
| 9 | | | 45.68164 | 1500.340 |
| 10 | | | 88.94922 | 1600.353 |
| 11 | | | 161.90322 | 1700.382 |
| 2nd run | | | | |
| 1 | 0.19810 | 961.955 | | |
| 2 | 0.33766 | 999.836 | | |
| 3 | | | | |
| 4 | 1.00092 | 1084.693 | | |
| 5 | 1.20209 | 1100.121 | | |
| 6 | 3.58770 | 1200.060 | | |
| 7 | 9.31871 | 1299.993 | 9.34106 | 1300.261 |
| 8 | 21.58624 | 1399.866 | 21.65148 | 1400.248 |
| 9 | | | 45.69071 | 1500.368 |
| 10 | | | 88.96758 | 1600.386 |
| 11 | | | 161.92887 | 1700.410 |
| 3rd run | | | | |
| 1 | 0.19818 | 961.983 | | |
| 2 | 0.33778 | 999.862 | | |
| 3 | 0.77937 | 1064.168 | | |
| 4 | 1.00168 | 1084.756 | | |

| | | | | |
|---|---|---|---|---|
| 5 | 1.20385 | 1100.246 | | |
| 6 | 3.59131 | 1200.158 | | |
| 7 | 9.32877 | 1300.114 | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 4th run | | | | |
| 1 | 0.19778 | 961.844 | | |
| 2 | 0.33740 | 999.780 | | |
| 3 | 0.77903 | 1064.133 | | |
| 4 | 1.00032 | 1084.643 | | |
| 5 | 1.20109 | 1100.050 | | |
| 6 | 3.58511 | 1199.989 | | |
| 7 | 9.31283 | 1299.923 | 9.30913 | 1299.878 |
| 8 | 21.57278 | 1399.787 | 21.57842 | 1399.820 |
| 9 | | | 45.57616 | 1500.012 |
| 10 | | | 88.73851 | 1599.977 |
| 11 | | | 161.46221 | 1699.902 |
| 5th run | | | | |
| 1 | 0.19765 | 961.799 | | |
| 2 | 0.33727 | 999.751 | | |
| 3 | 0.77842 | 1064.070 | | |
| 4 | 1.00043 | 1084.652 | | |
| 5 | 1.20115 | 1100.055 | | |
| 6 | 3.58554 | 1200.001 | | |
| 7 | 9.31812 | 1299.986 | 9.31765 | 1299.981 |
| 8 | 21.57851 | 1399.821 | 21.58775 | 1399.875 |
| 9 | | | 45.59129 | 1500.059 |
| 10 | | | 88.78035 | 1600.052 |
| 11 | | | 161.56236 | 1700.011 |

**Table A3:** Calibration after corrections for non-linearity

The correction factor for the ratio of photo current $i(t_\lambda) / i(t_{Cu})$ is expressed as $F_N = 1 - \Delta i / i$ where i is the total photo current and $\Delta i$ is that part of i due to the non-linearity.

For the large aperture, the correction factor is given by

$F_{NL} = 1 + (v - v^*)(0.000\,018\,97 + 0.001\,355\,17\, v + 0.001\,005\,17\, v^2 + 0.000\,225\,52\, v^3)$
(3)

For the small aperture, the correction factor is given by

$F_{NS} = 1 + (v - v^*)(0.000\,003\,08 + 0.000\,121\,36\, v + 0.000\,190\,44\, v^2 + 0.000\,073\,09\, v^3)$
(4)

where $v^* = -3 / 2.3$

and $\quad v = \{\ln[i(t_\lambda) / i(t_{Cu})] - 3\} / 2.3$

(5)

| | Large aperture | | | | Small aperture | | | | Large aperture | Small aperture |
|---|---|---|---|---|---|---|---|---|---|---|
| Index | Correction factor | Ratio of photo currents | Effective wavelength | Temperature | Corection factor | Ratio of photo currents | Effective wavelength | Temperature | Scaled photo current ratio | |
| j | $F_{NL}$<br>Using Eq. (3) | $i(t_\lambda) / i(t_{Cu})$<br>=<br>$F_{NL}$ x $i(t_\lambda) / i(t_{Cu})$ in Table A2 | $\lambda_e$<br>nm | $t_\lambda(\lambda_e; t_b; I_\ell)$<br>$^oC$ | $F_{NS}$<br>Using Eq. (4) | $i(t_\lambda) / i(t_{Cu})$<br>=<br>$F_{NS}$ x $i(t_\lambda) / i(t_{Cu})$ in Table A2 | $\lambda_e$<br>nm | $t_\lambda(\lambda_e; t_b; I_\ell)$<br>$^oC$ | v<br>Using Eq. (5) and $i(t_\lambda) / i(t_{Cu})$ in Table A2 | |
| 1st run | | | | | | | | | | |
| 1 | 1.00033 | 0.19821 | 650.034 | 961.994 | | | | | -2.00815 | |
| 2 | 1.00023 | 0.33779 | 650.028 | 999.864 | | | | | -1.77633 | |
| 3 | | | | | | | | | | |
| 4 | 1.00000 | 1.00102 | 650.016 | 1084.701 | | | | | -1.30390 | |
| 5 | 0.99996 | 1.20209 | 650.014 | 1100.121 | | | | | -1.22430 | |
| 6 | 0.99971 | 3.58605 | 650.002 | 1200.015 | | | | | -0.74898 | |
| 7 | 0.99968 | 9.31483 | 649.991 | 1299.947 | 0.99998 | 9.33935 | 649.991 | 1300.241 | -0.33394 | -0.33293 |
| 8 | | | | | 1.00001 | 21.64745 | 649.982 | 1400.224 | | 0.03256 |
| 9 | | | | | 1.00012 | 45.68726 | 649.973 | 1500.357 | | 0.35726 |
| 10 | | | | | 1.00035 | 88.98066 | 649.966 | 1600.409 | | 0.64699 |
| 11 | | | | | 1.00072 | 162.01945 | 649.959 | 1700.508 | | 0.90739 |
| 2nd run | | | | | | | | | | |
| 1 | 1.00033 | 0.19817 | 650.034 | 961.980 | | | | | -2.00825 | |
| 2 | 1.00023 | 0.33774 | 650.028 | 999.853 | | | | | -1.77639 | |
| 3 | | | | | | | | | | |
| 4 | 1.00000 | 1.00092 | 650.016 | 1084.693 | | | | | -1.30395 | |
| 5 | 0.99996 | 1.20204 | 650.014 | 1100.118 | | | | | -1.22432 | |
| 6 | 0.99971 | 3.58665 | 650.002 | 1200.031 | | | | | -0.74891 | |
| 7 | 0.99968 | 9.31573 | 649.991 | 1299.958 | 0.99998 | 9.34089 | 649.991 | 1300.259 | -0.33390 | -0.33286 |
| 8 | 1.00008 | 21.58804 | 649.982 | 1399.877 | 1.00001 | 21.65169 | 649.982 | 1400.249 | 0.03133 | 0.03264 |
| 9 | | | | | 1.00012 | 45.69634 | 649.973 | 1500.386 | | 0.35735 |
| 10 | | | | | 1.00035 | 88.99903 | 649.966 | 1600.442 | | 0.64707 |
| 11 | | | | | 1.00072 | 162.04514 | 649.959 | 1700.536 | | 0.90746 |
| 3rd run | | | | | | | | | | |
| 1 | 1.00002 | 0.19819 | 650.034 | 961.987 | | | | | | |
| 2 | 1.00023 | 0.33786 | 650.028 | 999.879 | | | | | -1.77624 | |
| 3 | 1.00006 | 0.77941 | 650.019 | 1064.173 | | | | | -1.41273 | |
| 4 | 1.00000 | 1.00168 | 650.016 | 1084.756 | | | | | -1.30362 | |
| 5 | 0.99996 | 1.20380 | 650.014 | 1100.242 | | | | | -1.22368 | |
| 6 | 0.99971 | 3.59026 | 650.002 | 1200.130 | | | | | -0.74847 | |
| 7 | 0.99968 | 9.32579 | 649.991 | 1300.078 | | | | | -0.33343 | |
| 8 | | | | | | | | | | |
| 9 | | | | | | | | | | |
| 10 | | | | | | | | | | |
| 11 | | | | | | | | | | |
| 4th run | | | | | | | | | | |
| 1 | 1.00033 | 0.19784 | 650.034 | 961.865 | | | | | -2.00897 | |
| 2 | 1.00023 | 0.33748 | 650.028 | 999.797 | | | | | -1.77673 | |
| 3 | 1.00006 | 0.77907 | 650.019 | 1064.137 | | | | | -1.41292 | |
| 4 | 1.00000 | 1.00032 | 650.016 | 1084.643 | | | | | -1.30421 | |
| 5 | 0.99996 | 1.20103 | 650.014 | 1100.046 | | | | | -1.22468 | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 0.99971 | 3.58406 | 650.002 | 1199.960 | | | | | -0.74922 | |
| 7 | 0.99968 | 9.30985 | 649.991 | 1299.887 | 0.99998 | 9.30896 | 649.991 | 1299.876 | -0.33418 | -0.33435 |
| 8 | 1.00008 | 21.57456 | 649.982 | 1399.798 | 1.00001 | 21.57863 | 649.982 | 1399.822 | 0.03106 | 0.03117 |
| 9 | | | | | 1.00012 | 45.58175 | 649.973 | 1500.029 | | 0.35625 |
| 10 | | | | | 1.00035 | 88.76978 | 649.966 | 1600.033 | | 0.64595 |
| 11 | | | | | 1.00072 | 161.57780 | 649.959 | 1700.028 | | 0.90620 |

5th run

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00034 | 0.19771 | 650.034 | 961.820 | | | | | -2.00925 | |
| 2 | 1.00023 | 0.33735 | 650.028 | 999.769 | | | | | -1.77690 | |
| 3 | 1.00006 | 0.77846 | 650.019 | 1064.074 | | | | | -1.41326 | |
| 4 | 1.00000 | 1.00043 | 650.016 | 1084.652 | | | | | -1.30416 | |
| 5 | 0.99996 | 1.20109 | 650.014 | 1100.050 | | | | | -1.22466 | |
| 6 | 0.99971 | 3.58449 | 650.002 | 1199.972 | | | | | -0.74917 | |
| 7 | 0.99968 | 9.31513 | 649.991 | 1299.950 | 0.99998 | 9.31748 | 649.991 | 1299.979 | -0.33393 | -0.33395 |
| 8 | 1.00008 | 21.58031 | 649.982 | 1399.832 | 1.00001 | 21.58796 | 649.982 | 1399.876 | 0.03117 | 0.03136 |
| 9 | | | | | 1.00012 | 45.59688 | 649.973 | 1500.076 | | 0.35640 |
| 10 | | | | | 1.00035 | 88.81165 | 649.966 | 1600.108 | | 0.64616 |
| 11 | | | | | 1.00072 | 161.67810 | 649.959 | 1700.137 | | 0.90647 |

**Table B1:** Calibration after corrections for wavelength

From "Protocol" by P. Bloembergen:

$(\partial t_\lambda / \partial \lambda)$ / (°C / nm) = $- 0.35422504 \times 10^{-1} + 2.70716088 \times 10^{-5}\, t_\lambda$ / °C $- 0.10980270 \times 10^{-6}\, (t_\lambda$ / °C$)^2$ (6)

Reference wavelength $\lambda_r = 650$ nm

| | Large aperture | | | | Small aperture | | | |
|---|---|---|---|---|---|---|---|---|
| Index<br>j | Sensitivity<br>$\partial t_\lambda / \partial \lambda$<br>Using Eq. (6) and $t_\lambda$ in Table A3<br>°C / nm | Wavelength difference<br>$\Delta\lambda =$<br>$\lambda_r - \lambda_e$ in Table A3<br>nm | Wavelength correction<br>$\Delta t =$<br>$\partial t_\lambda / \partial\lambda \times \Delta\lambda$<br>°C | Temperature<br>$t_\lambda(\lambda_r; t_b; I_\ell) =$<br>$t_\lambda(\lambda_e; t_b; I_\ell)$ in Table A3 $+ \Delta t$<br>°C | Sensitivity<br>$\partial t_\lambda / \partial \lambda$<br>Using Eq. (6) and $t_\lambda$ in Table A3<br>°C / nm | Wavelength difference<br>$\Delta\lambda =$<br>$\lambda_r - \lambda_e$ in Table A3<br>nm | Wavelength correction<br>$\Delta t =$<br>$\partial t_\lambda / \partial\lambda \times \Delta\lambda$<br>°C | Temperature<br>$t_\lambda(\lambda_r; t_b; I_\ell) =$<br>$t_\lambda(\lambda_e; t_b; I_\ell)$ in Table A3 $+ \Delta t$<br>°C |
| 1st run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 961.998 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.867 | | | | |
| 3 | | | | | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.703 | | | | |
| 5 | -0.139 | -0.014 | 0.002 | 1100.123 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1200.015 | | | | |
| 7 | -0.186 | 0.009 | -0.002 | 1299.945 | -0.186 | 0.009 | -0.002 | 1300.239 |
| 8 | | | | | -0.213 | 0.018 | -0.004 | 1400.220 |
| 9 | | | | | -0.242 | 0.027 | -0.007 | 1500.350 |
| 10 | | | | | -0.273 | 0.034 | -0.009 | 1600.400 |
| 11 | | | | | -0.307 | 0.041 | -0.013 | 1700.495 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2nd run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 961.984 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.856 | | | | |
| 3 | | | | | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.695 | | | | |
| 5 | -0.139 | -0.014 | 0.002 | 1100.120 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1200.031 | | | | |
| 7 | -0.186 | 0.009 | -0.002 | 1299.956 | -0.186 | 0.009 | -0.002 | 1300.257 |
| 8 | -0.213 | 0.018 | -0.004 | 1399.873 | -0.213 | 0.018 | -0.004 | 1400.245 |
| 9 | | | | | -0.242 | 0.027 | -0.007 | 1500.379 |
| 10 | | | | | -0.273 | 0.034 | -0.009 | 1600.433 |
| 11 | | | | | -0.307 | 0.041 | -0.013 | 1700.523 |
| 3rd run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 961.991 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.882 | | | | |
| 3 | -0.131 | -0.019 | 0.002 | 1064.175 | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.758 | | | | |
| 5 | -0.139 | -0.014 | 0.002 | 1100.244 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1200.130 | | | | |
| 7 | -0.186 | 0.009 | -0.002 | 1300.076 | | | | |
| 8 | | | | | | | | |
| 9 | | | | | | | | |
| 10 | | | | | | | | |
| 11 | | | | | | | | |
| 4th run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 961.869 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.800 | | | | |
| 3 | -0.131 | -0.019 | 0.002 | 1064.139 | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.645 | | | | |
| 5 | -0.139 | -0.014 | 0.002 | 1100.048 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1199.960 | | | | |
| 7 | -0.186 | 0.009 | -0.002 | 1299.885 | -0.186 | 0.009 | -0.002 | 1299.874 |
| 8 | -0.213 | 0.018 | -0.004 | 1399.794 | -0.213 | 0.018 | -0.004 | 1399.818 |
| 9 | | | | | -0.242 | 0.027 | -0.007 | 1500.022 |
| 10 | | | | | -0.273 | 0.034 | -0.009 | 1600.024 |
| 11 | | | | | -0.307 | 0.041 | -0.013 | 1700.015 |
| 5th run | | | | | | | | |
| 1 | -0.111 | -0.034 | 0.004 | 961.824 | | | | |
| 2 | -0.118 | -0.028 | 0.003 | 999.772 | | | | |
| 3 | -0.131 | -0.019 | 0.002 | 1064.076 | | | | |
| 4 | -0.135 | -0.016 | 0.002 | 1084.654 | | | | |
| 5 | -0.139 | -0.014 | 0.002 | 1100.052 | | | | |
| 6 | -0.161 | -0.002 | 0.000 | 1199.972 | | | | |
| 7 | -0.186 | 0.009 | -0.002 | 1299.948 | -0.186 | 0.009 | -0.002 | 1299.977 |
| 8 | -0.213 | 0.018 | -0.004 | 1399.828 | -0.213 | 0.018 | -0.004 | 1399.872 |
| 9 | | | | | -0.242 | 0.027 | -0.007 | 1500.069 |
| 10 | | | | | -0.273 | 0.034 | -0.009 | 1600.099 |
| 11 | | | | | -0.307 | 0.041 | -0.013 | 1700.124 |

**Table B2:** Calibration after corrections for the temperature of the lamp base

Reference temperature for the lamp base $t_r$ = 20°C

For 961.78°C ≤ $t_\lambda$ ≤ 1200°C, $\partial t_\lambda / \partial t_b = 0.0354 - 0.0465\, w + 0.0216\, w^2$ (7)
where $w = (t_\lambda / °C - 1080) / 120$ (8)

For $t_\lambda$ ~ 1300°C, $\partial t_\lambda / \partial t_b = 0.005$
For $t_\lambda$ ~ 1400°C, $\partial t_\lambda / \partial t_b = 0.002$
For $t_\lambda$ ~ 1500°C and higher, $\partial t_\lambda / \partial t_b = 0.000$

| | | Large aperture | | | | Small aperture | | | | Large aperture | Small aperture |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Index | Current | Sensitivity | Base temperature difference | Base temperature correction | Temperature | Sensitivity | Base temperature difference | Base temperature correction | Temperature | Scaled temperature | |
| $j$ | $I_\ell$ | $\partial t_\lambda / \partial t_b$ | $\Delta t_b$ = | $\Delta t$ = | $t_\lambda(\lambda_r; t_r; I_\ell)$ = | $\partial t_\lambda / \partial t_b$ | $\Delta t_b$ = | $\Delta t$ = | $t_\lambda(\lambda_r; t_r; I_\ell)$ = | $w$ | |
| | From Table I<br>A | Using Eq. (7) or assigned values given above | $t_r - t_b$ in Table I<br>°C | $\partial t_\lambda / \partial t_b \times \Delta t_b$<br>°C | $t_\lambda(\lambda_r; t_b; I_\ell)$ in Table B1 + $\Delta t$<br>°C | Using assigned values given above | $t_r - t_b$ in Table I<br>°C | $\partial t_\lambda / \partial t_b \times \Delta t_b$<br>°C | $t_\lambda(\lambda_r; t_b; I_\ell)$ in Table B1 + $\Delta t$<br>°C | Using Eq. (8) and $t_\lambda$ in Table B1 | |
| 1st run | | | | | | | | | | | |
| 1 | 5.18290 | 0.102 | 0.011 | 0.001 | 961.999 | | | | | -0.98335 | |
| 2 | 5.45445 | 0.076 | 0.011 | 0.001 | 999.868 | | | | | -0.66777 | |
| 3 | | | | | | | | | | | |
| 4 | 6.13825 | 0.034 | 0.019 | 0.001 | 1084.704 | | | | | 0.03919 | |
| 5 | 6.27330 | 0.028 | -0.005 | 0.000 | 1100.123 | | | | | 0.16769 | |
| 6 | 7.21982 | 0.010 | -0.020 | 0.000 | 1200.015 | | | | | 1.00013 | |
| 7 | 8.27214 | 0.005 | -0.081 | 0.000 | 1299.945 | 0.005 | -0.081 | 0.000 | 1300.239 | 1.83288 | 1.83533 |
| 8 | 9.40735 | | | | | 0.002 | -0.110 | 0.000 | 1400.220 | | 2.66850 |
| 9 | 10.61192 | | | | | 0.000 | -0.165 | 0.000 | 1500.350 | | 3.50292 |
| 10 | 11.87454 | | | | | 0.000 | -0.218 | 0.000 | 1600.400 | | 4.33666 |
| 11 | 13.19122 | | | | | 0.000 | -0.264 | 0.000 | 1700.495 | | 5.17080 |
| 2nd run | | | | | | | | | | | |
| 1 | 5.18286 | 0.102 | -0.015 | -0.002 | 961.982 | | | | | -0.98347 | |
| 2 | 5.45445 | 0.076 | -0.015 | -0.001 | 999.855 | | | | | -0.66786 | |
| 3 | | | | | | | | | | | |
| 4 | 6.13826 | 0.034 | -0.035 | -0.001 | 1084.694 | | | | | 0.03913 | |
| 5 | 6.27331 | 0.028 | -0.043 | -0.001 | 1100.119 | | | | | 0.16767 | |
| 6 | 7.21980 | 0.010 | -0.074 | -0.001 | 1200.031 | | | | | 1.00026 | |
| 7 | 8.27214 | 0.005 | -0.128 | -0.001 | 1299.956 | 0.005 | -0.128 | -0.001 | 1300.257 | 1.83297 | 1.83548 |
| 8 | 9.40735 | 0.002 | -0.143 | 0.000 | 1399.873 | 0.002 | -0.143 | 0.000 | 1400.245 | 2.66561 | 2.66871 |
| 9 | 10.61192 | | | | | 0.000 | -0.187 | 0.000 | 1500.379 | | 3.50316 |
| 10 | 11.87447 | | | | | 0.000 | -0.225 | 0.000 | 1600.433 | | 4.33694 |
| 11 | 13.19120 | | | | | 0.000 | -0.274 | 0.000 | 1700.523 | | 5.17103 |
| 3rd run | | | | | | | | | | | |
| 1 | 5.18290 | 0.102 | 0.019 | 0.002 | 961.993 | | | | | -0.98341 | |
| 2 | 5.45448 | 0.076 | 0.011 | 0.001 | 999.883 | | | | | -0.66765 | |
| 3 | 5.96316 | 0.042 | 0.000 | 0.000 | 1064.175 | | | | | -0.13187 | |
| 4 | 6.13828 | 0.034 | -0.033 | -0.001 | 1084.757 | | | | | 0.03965 | |
| 5 | 6.27332 | 0.028 | 0.034 | 0.001 | 1100.245 | | | | | 0.16870 | |
| 6 | 7.21981 | 0.010 | -0.004 | 0.000 | 1200.130 | | | | | 1.00109 | |
| 7 | 8.27215 | 0.005 | -0.102 | -0.001 | 1300.076 | | | | | | |
| 8 | | | | | | | | | | | |
| 9 | | | | | | | | | | | |
| 10 | | | | | | | | | | | |
| 11 | | | | | | | | | | | |
| 4th run | | | | | | | | | | | |
| 1 | 5.18288 | 0.102 | -0.200 | -0.020 | 961.848 | | | | | -0.98443 | |
| 2 | 5.45477 | 0.076 | -0.212 | -0.016 | 999.784 | | | | | -0.66833 | |
| 3 | 5.96350 | 0.042 | -0.254 | -0.011 | 1064.129 | | | | | -0.13217 | |
| 4 | 6.13856 | 0.034 | -0.259 | -0.009 | 1084.636 | | | | | 0.03871 | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 6.27343 | 0.028 | -0.269 | -0.008 | 1100.040 | | | | | 0.16707 | |
| 6 | 7.21982 | 0.011 | -0.323 | -0.003 | 1199.957 | | | | | 0.99967 | |
| 7 | 8.27204 | 0.005 | -0.417 | -0.002 | 1299.883 | 0.005 | -0.417 | -0.002 | 1299.872 | 1.83238 | 1.83229 |
| 8 | 9.40688 | 0.002 | -0.508 | -0.001 | 1399.793 | 0.002 | -0.508 | -0.001 | 1399.817 | 2.66495 | 2.66515 |
| 9 | 10.61270 | | | | | 0.000 | -0.606 | 0.000 | 1500.022 | | 3.50019 |
| 10 | 11.87282 | | | | | 0.000 | -0.724 | 0.000 | 1600.024 | | 4.33353 |
| 11 | 13.19125 | | | | | 0.000 | -0.842 | 0.000 | 1700.015 | | 5.16680 |
| 5th run | | | | | | | | | | | |
| 1 | 5.18277 | 0.102 | -0.256 | -0.026 | 961.798 | | | | | -0.98480 | |
| 2 | 5.45466 | 0.076 | -0.310 | -0.024 | 999.749 | | | | | -0.66856 | |
| 3 | 5.96342 | 0.042 | -0.336 | -0.014 | 1064.062 | | | | | -0.13270 | |
| 4 | 6.13839 | 0.034 | -0.374 | -0.013 | 1084.642 | | | | | 0.03878 | |
| 5 | 6.27326 | 0.028 | -0.387 | -0.011 | 1100.041 | | | | | 0.16710 | |
| 6 | 7.21971 | 0.011 | -0.428 | -0.004 | 1199.968 | | | | | 0.99977 | |
| 7 | 8.27241 | 0.005 | -0.512 | -0.003 | 1299.946 | 0.005 | -0.512 | -0.003 | 1299.975 | 1.83290 | 1.83314 |
| 8 | 9.40690 | 0.002 | -0.601 | -0.001 | 1399.827 | 0.002 | -0.601 | -0.001 | 1399.871 | 2.66523 | 2.66560 |
| 9 | 10.61236 | | | | | 0.000 | -0.690 | 0.000 | 1500.069 | | 3.50058 |
| 10 | 11.87486 | | | | | 0.000 | -0.791 | 0.000 | 1600.099 | | 4.33416 |
| 11 | 13.19128 | | | | | 0.000 | -0.870 | 0.000 | 1700.124 | | 5.16770 |

**Table B3:** Calibration in terms of radiance temperature as a function of lamp current at the reference wavelength and lamp-base temperature

A polynomial is fitted to the data of $t_\lambda$ and $I_\lambda$ for the 1st, 2nd and 3rd runs in Table B2 (data before the departure of the lamp to PTB) to express $t_\lambda$ as a function of $I_\lambda$.

Another polynomial is fitted to the data for the 4th and 5th runs (data after the return of the lamp from PTB).

For the 1st, 2nd and 3rd runs,

$$t_\lambda / °C = 1364.9563 + 348.9149\, z - 37.8154\, z^2 + 18.3207\, z^3 - 9.9394\, z^4 + 2.2404\, z^5 - 6.8364\, z^6 + 6.2010\, z^7 \tag{9}$$

For the 4th and 5th runs,

$$t_\lambda / °C = 1364.7364 + 348.6177\, z - 38.0963\, z^2 + 18.0661\, z^3 - 8.9975\, z^4 + 3.9923\, z^5 - 7.5011\, z^6 + 4.9177\, z^7 \tag{10}$$

$$\text{where} \quad z = (I_\lambda / A - 9) / 4 \tag{11}$$

and $961.78 \le t_\lambda / °C \le 1700$

| Index<br><br>j | Current: Absolute<br><br>$I_\ell$<br><br>From Table B2<br><br>A | Current: Scaled<br><br>z<br><br>Using Eq. (11) | Temperature Computed<br><br>$t_\lambda(\lambda_r; t_r; I_\ell)$<br><br>Using Eq. (9) or (10)<br><br>°C | Large aperture: Temperature Measured<br><br>$t_\lambda(\lambda_r; t_r; I_\ell)$<br><br>From Table B2<br><br>°C | Large aperture: Residual<br><br>$\Delta t_\lambda$<br><br>Computed - Measured<br><br>°C | Small aperture: Temperature Measured<br><br>$t_\lambda(\lambda_r; t_r; I_\ell)$<br><br>From Table B2<br><br>°C | Small aperture: Residual<br><br>$\Delta t_\lambda$<br><br>Computed - Measured<br><br>°C |
|---|---|---|---|---|---|---|---|
| 1st run | | | | | | | |
| 1 | 5.18290 | -0.954275 | 961.992 | 961.999 | -0.007 | | |
| 2 | 5.45445 | -0.886388 | 999.870 | 999.868 | 0.002 | | |
| 3 | | | | | | | |
| 4 | 6.13825 | -0.715438 | 1084.729 | 1084.704 | 0.025 | | |
| 5 | 6.27330 | -0.681675 | 1100.148 | 1100.123 | 0.026 | | |
| 6 | 7.21982 | -0.445045 | 1200.065 | 1200.015 | 0.050 | | |
| 7 | 8.27214 | -0.181965 | 1300.092 | 1299.945 | 0.147 | 1300.239 | -0.147 |
| 8 | 9.40735 | 0.101838 | 1400.115 | | | 1400.220 | -0.105 |
| 9 | 10.61192 | 0.402980 | 1500.363 | | | 1500.350 | 0.013 |
| 10 | 11.87454 | 0.718635 | 1600.420 | | | 1600.400 | 0.020 |
| 11 | 13.19122 | 1.047805 | 1700.510 | | | 1700.495 | 0.014 |
| 2nd run | | | | | | | |
| 1 | 5.18286 | -0.954285 | 961.986 | 961.982 | 0.004 | | |
| 2 | 5.45445 | -0.886388 | 999.870 | 999.855 | 0.015 | | |
| 3 | | | | | | | |
| 4 | 6.13826 | -0.715435 | 1084.730 | 1084.694 | 0.036 | | |
| 5 | 6.27331 | -0.681673 | 1100.149 | 1100.119 | 0.031 | | |
| 6 | 7.21980 | -0.445050 | 1200.063 | 1200.031 | 0.032 | | |
| 7 | 8.27214 | -0.181965 | 1300.092 | 1299.956 | 0.136 | 1300.257 | -0.165 |
| 8 | 9.40735 | 0.101838 | 1400.115 | 1399.873 | 0.242 | 1400.245 | -0.130 |
| 9 | 10.61192 | 0.402980 | 1500.363 | | | 1500.379 | -0.016 |
| 10 | 11.87447 | 0.718618 | 1600.414 | | | 1600.433 | -0.019 |
| 11 | 13.19120 | 1.047800 | 1700.508 | | | 1700.523 | -0.015 |
| 3rd run | | | | | | | |
| 1 | 5.18290 | -0.954275 | 961.992 | 961.993 | -0.001 | | |
| 2 | 5.45448 | -0.886380 | 999.874 | 999.883 | -0.009 | | |
| 3 | 5.96316 | -0.759210 | 1064.164 | 1064.175 | -0.011 | | |
| 4 | 6.13828 | -0.715430 | 1084.732 | 1084.757 | -0.025 | | |
| 5 | 6.27332 | -0.681670 | 1100.151 | 1100.245 | -0.094 | | |
| 6 | 7.21981 | -0.445048 | 1200.064 | 1200.130 | -0.066 | | |
| 7 | 8.27215 | -0.181963 | 1300.093 | 1300.076 | 0.017 | | |
| 8 | | | | | | | |
| 9 | | | | | | | |
| 10 | | | | | | | |
| 11 | | | | | | | |
| 4th run | | | | | | | |
| 1 | 5.18288 | -0.954280 | 961.836 | 961.848 | -0.013 | | |
| 2 | 5.45477 | -0.886308 | 999.765 | 999.784 | -0.019 | | |
| 3 | 5.96350 | -0.759125 | 1064.091 | 1064.129 | -0.038 | | |
| 4 | 6.13856 | -0.715360 | 1084.659 | 1084.636 | 0.023 | | |
| 5 | 6.27343 | -0.681643 | 1100.062 | 1100.040 | 0.022 | | |
| 6 | 7.21982 | -0.445045 | 1199.950 | 1199.957 | -0.007 | | |
| 7 | 8.27204 | -0.181990 | 1299.910 | 1299.883 | 0.027 | 1299.872 | 0.038 |
| 8 | 9.40688 | 0.101720 | 1399.822 | 1399.793 | 0.029 | 1399.817 | 0.005 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | 10.61270 | 0.403175 | 1500.063 | | | 1500.022 | 0.040 |
| 10 | 11.87282 | 0.718205 | 1599.982 | | | 1600.024 | -0.042 |
| 11 | 13.19125 | 1.047813 | 1700.068 | | | 1700.015 | 0.053 |
| 5th run | | | | | | | |
| 1 | 5.18277 | -0.954308 | 961.820 | 961.798 | 0.022 | | |
| 2 | 5.45466 | -0.886335 | 999.750 | 999.749 | 0.002 | | |
| 3 | 5.96342 | -0.759145 | 1064.081 | 1064.062 | 0.019 | | |
| 4 | 6.13839 | -0.715403 | 1084.640 | 1084.642 | -0.002 | | |
| 5 | 6.27326 | -0.681685 | 1100.043 | 1100.041 | 0.002 | | |
| 6 | 7.21971 | -0.445073 | 1199.939 | 1199.968 | -0.029 | | |
| 7 | 8.27241 | -0.181898 | 1299.944 | 1299.946 | -0.002 | 1299.975 | -0.031 |
| 8 | 9.40690 | 0.101725 | 1399.823 | 1399.827 | -0.004 | 1399.871 | -0.048 |
| 9 | 10.61236 | 0.403090 | 1500.035 | | | 1500.069 | -0.034 |
| 10 | 11.87486 | 0.718715 | 1600.140 | | | 1600.099 | 0.041 |
| 11 | 13.19128 | 1.047820 | 1700.071 | | | 1700.124 | -0.054 |

The deviation of Eq. (10) from Eq. (9) is taken to be the change of calibration after the return of the lamp from PTB:

$$\Delta t_\lambda \,/\, °C = -0.2199 - 0.2972\, z - 0.2809\, z^2 - 0.2546\, z^3 + 0.9419\, z^4 + 1.7519\, z^5 - 0.6647\, z^6 - 1.2833\, z^7 \qquad (12)$$

The changes at the reference lamp currents are given in the following table:

| Index | Lamp Current | | Nominal temperature | Temperature change |
|---|---|---|---|---|
| | Absolute | Scaled | | |
| j | $I_\ell$ | z | $t_\lambda$ | $\Delta t_\lambda$ |
| | A | Using Eq. (11) | $^oC$ | $^oC$ |
| | From Table A1 | | | Using Eq. (12) |
| 1 | 5.185 | -0.953750 | 961.780 | -0.153 |
| 2 | 5.457 | -0.885750 | 1000.000 | -0.148 |
| 3 | 5.966 | -0.758500 | 1064.180 | -0.114 |
| 4 | 6.141 | -0.714750 | 1084.620 | -0.105 |
| 5 | 6.276 | -0.681000 | 1100.000 | -0.101 |
| 6 | 7.223 | -0.444250 | 1200.000 | -0.115 |
| 7 | 8.276 | -0.181000 | 1300.000 | -0.173 |
| 8 | 9.411 | 0.102750 | 1400.000 | -0.254 |
| 9 | 10.617 | 0.404250 | 1500.000 | -0.364 |
| 10 | 11.880 | 0.720000 | 1600.000 | -0.304 |
| 11 | 13.197 | 1.049250 | 1700.000 | -0.449 |

The mean of Eqs. (9) and (10) is taken to be the analytical representation of the calibration of the lamp:

$$t_\lambda \,/\, °C = 1364.8464 + 348.7663\, z - 37.9559\, z^2 + 18.1934\, z^3 - 9.4685\, z^4 + 3.1164\, z^5 - 7.1688\, z^6 + 5.5594\, z^7 \qquad (13)$$

where z is a (non-dimensionalized) lamp current after scaling according to Eq. (11)

To facilitate comparison at the reference currents the following table is given:

| Index | Lamp Current | | Temperature |
|---|---|---|---|
| | Absolute | Scaled | |
| j | $I_\ell$ | z | $t_\lambda(\lambda_r; t_r; I_\ell)$ |
| | From Table A1 | Using Eq. (11) | Using Eq. (13) |
| | A | | $^oC$ |
| 1 | 5.185 | -0.953750 | 962.220 |
| 2 | 5.457 | -0.885750 | 1000.138 |
| 3 | 5.966 | -0.758500 | 1064.446 |
| 4 | 6.141 | -0.714750 | 1084.994 |
| 5 | 6.276 | -0.681000 | 1100.403 |
| 6 | 7.223 | -0.444250 | 1200.324 |
| 7 | 8.276 | -0.181000 | 1300.357 |
| 8 | 9.411 | 0.102750 | 1400.300 |
| 9 | 10.617 | 0.404250 | 1500.594 |
| 10 | 11.880 | 0.720000 | 1600.690 |
| 11 | 13.197 | 1.049250 | 1700.724 |