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REPORT ON THE NPL MEASUREMENTS FOR THE CCT K10 COMPARISON, SEPTEMBER 2014 TO JANUARY 2020

HELEN MCEVOY, DAVE LOWE, GRAHAM MACHIN, AARON WHITTAM, MICHAEL HAYES

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REPORT ON THE NPL MEASUREMENTS FOR THE CCT-K10 COMPARISON, FROM AUGUST 2014 TO JANUARY 2020

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Thermal and Radiometric Metrology

ABSTRACT

This report outlines the equipment, measurement method, results and uncertainties associated with the NPL measurements for the Consultative Committee of Thermometry Key Comparison K10 (CCT-K10), "ITS-90 realisations above the silver point using two transfer radiation thermometers and a set of high temperature fixed-point blackbody cells", over the period from August 2014 to the final measurements made during January 2020.

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1 INTRODUCTION

This report summarises the measurements made at NPL (as the pilot laboratory) of the circulating devices for the CCT-K10 comparison, which is a Key Comparison at high temperatures above the silver point using radiation thermometry. It provides the data and information in the agreed format that, when collated with data from the other participants, will allow the final analysis of results to be carried out.

The circulating instruments for the CCT-K10 comparison were: KE Technologie LP3 radiation thermometer, Chino IR-RST65 radiation thermometer, Chino copper (Cu) fixed-point source, and high temperature fixed points (HTFPs) of Ni-C-X, Co-C-X, Ru-C and WC-C. The main comparison report has more details of the instruments.

The measurements that were performed at NPL were: calibration of the two transfer radiation thermometers over the temperature range from 962 °C to 3000 °C according to the CCT-K10 protocol; measurement of the HTFPs, including comparisons between the circulating and reference cells; measurement of the size-of-source effect and non-linearity of the two transfer thermometers; measurement of the spectral response of the KE LP3 thermometer; and comparison of the transfer Cu fixed point with the NPL copper (Cu) fixed-point blackbody.

2 GENERAL INFORMATION

2.1 DESCRIPTION OF EQUIPMENT

The following equipment was used to perform the NPL measurements.

2.1.1 High temperature blackbody source for the radiation thermometer calibration

Manufacturer : Thermo Gauge Instruments Inc.
Type/ model : HT−9500 with HT-7050 controller
Serial number : 950501
Aperture : 25 mm diameter cavity

2.1.2 Reference thermometer for the radiation thermometer calibration

Manufacturer : KE Technologie GmbH
Type/ model : Linear Pyrometer LP3
Serial number : 80-49
Spot size : nominally 1 mm at 820 mm working distance
Wavelengths : nominally 650 nm and 900 nm (650 nm only at and above 2800 °C)

2.1.3 High temperature furnace used for WC-C measurements

Thermo Gauge furnace as above (2.1.1) with bored-out blackbody tube.

2.1.4 High temperature furnace for Ru-C, Ni-C and Co-C measurements

Thermo Gauge furnace as above (2.1.1) with bored-out blackbody tube
or the following Chino Corporation furnace (e.g., when the Thermo Gauge furnace was unavailable) as follows:

Manufacturer : Chino Corporation
Type/ model : IR-R80
Serial number : AX082PA01

2.1.5 Reference thermometer for the HTFP measurements

KE Linear Pyrometer LP3 as above (2.1.2)

3 MEASUREMENT METHODOLOGY

3.1.1 Calibration of the KC transfer radiation thermometers

The working distance of the thermometers was as prescribed in the protocol, i.e., 750 mm for the LP3 and 700 mm for the Chino thermometer, which was measured from the front of the thermometer casing.

The transfer thermometers were checked using the transfer Chino Cu fixed point both at the start of the NPL measurements and at the end, prior to being packed up for shipment. The measurements were carried out according to the comparison protocol[1] with the transfer thermometers set at the specified working distance to the Cu fixed-point aperture.

The KC transfer thermometers were then each calibrated using the same method. Each thermometer was set at the prescribed working distance from the back wall of the Thermo Gauge cavity (750 mm for the KC LP3 and 700 mm for the Chino thermometer). Each was aligned and focused on the centre of the cavity back wall. The NPL standard LP3 was set at its prescribed working distance (nominally 820 mm) from the Thermo Gauge cavity back wall and also aligned on the centre of the back wall. (It should be noted that the NPL LP3 essentially operates as a fixed focus device, with the focus control locked and the focusing achieved by adjusting the distance between the instrument and the target).

The NPL LP3 has been characterised according to the scheme of the International Temperature Scale of 1990 (the ITS-90). In other words, it has been assessed and characterised in terms of linearity, size-of-source effect and its spectral response. It is periodically calibrated using a blackbody cavity at the freezing point of Cu [1] in order to determine the reference photocurrent I_{ph}(Cu). Radiance temperatures of a source at the unknown temperature T_x are subsequently determined from the measured photocurrent I_{ph} (T_x) using the reference photocurrent and the mean effective wavelength $\lambda_{Cu,x}$ (calculated from the effective wavelengths at T_{Cu} and T_x determined from the spectral response), using Planck's law in ratio form:

$$T_x = \frac{c_2}{\lambda_{Cu,x} ln\left[1 + \frac{I_{ph}(Cu)}{I_{ph}(T_x)}\left(exp\left(\frac{c_2}{\lambda_{Cu,x}T_{Cu}}\right) - 1\right)\right]} \quad (1)$$

The calibration of the KC thermometers was performed by setting the blackbody to the required calibration temperature and allowing it to stabilise. A series of measurements of the radiance temperature were made using, alternately, both the KC transfer thermometer and the NPL LP3. The background (dark current) signal was measured and subtracted from each of the thermometer readings.

Horizontal and vertical thermal uniformity profile scans of the cavity were also carried out in order to assess the temperature uniformity of the cavity back wall. This was to allow an uncertainty component to be estimated to take into account both any differences in the alignment of the KC and NPL LP3 thermometers on the back wall, and for differences in spot size of the KC thermometers and the LP3.

1 the exception to this is during the January 2020 measurements where, for technical reasons, the NPL Cu fixed point was used instead of the transfer Cu fixed point, and only a measurement at the end of the NPL measurements was performed

For each of the calibration runs, the calibration was carried out at the temperatures specified in the protocol. Repeat calibration measurements were carried out at at least three temperatures over the calibration range. During the calibration the range and gain ratios were measured for both the KC LP3 and the Chino thermometer with the blackbody held at an appropriate temperature or temperatures. The transmission of the neutral filter of the KC LP3 was also measured at a blackbody temperature of (nominally) 2400 °C.

3.1.2 The measurement of the HTFP cells

Prior to the measurements of the cells the furnace(s), furnace tubes and insulation material etc. were baked out as necessary. The cells were installed in the furnace with appropriate insulation. For example, for WC-C measurements in the NPL Thermo Gauge furnace the cells were wrapped in PERMA-FOIL®[2] with, alternately, carbon-carbon composite (CC) discs and pieces of rigid graphite foam front and back of the cell. For measurements in the Chino furnace, the cell was wrapped in graphite tape and graphite string and alternating CC discs and graphite foam spacers were placed front and back of the cell, as the manufacturer's specification. Figure 1 shows an example of an HTFP arrangement.

Figure 1 - example set up for a HTFP cell

Melting and freezing was carried out by raising or lowering the furnace temperature in steps of nominally ± 20 °C from the melting transition temperature.

Measurements of the cells were made with the NPL LP3. Thermal profile scans were carried out during melting, to allow any differences in radiance profile between NPL and other participants to be taken into account.

3.2 AUXILIARY MEASUREMENTS OF THE TWO KC TRANSFER THERMOMETERS

In addition to the main calibration measurements the following auxiliary measurements were carried out for the two KC transfer thermometers. These were measurements of the non-linearity and size-of-source effect (SSE) of both thermometers and the spectral response of the KC LP3.

3.2.1 Non-linearity measurements

The non-linearity measurements were carried out using the Thermo Gauge high temperature furnace and using an NPL-made non-linearity device which was screwed onto the objective nose of the KC

2 Toyo Tanso PERMA-FOIL®UHP 99.999% pure flexible graphite 0.43 mm thick

thermometer using the thread on the inside of the objective nose (with due care taken not to touch the front lens of the thermometer). For the KC LP3 measurements the non-linearity device was the one made for the NPL LP3; for the Chino thermometer the device was one made for an NPL-designed standard radiation thermometer which, fortuitously, had an objective nose of the same diameter as the Chino thermometer and with the same internal thread size. A photograph of the non-linearity device for the Chino thermometer is shown in Figure 2 below. The LP3 non-linearity device is of the same design.

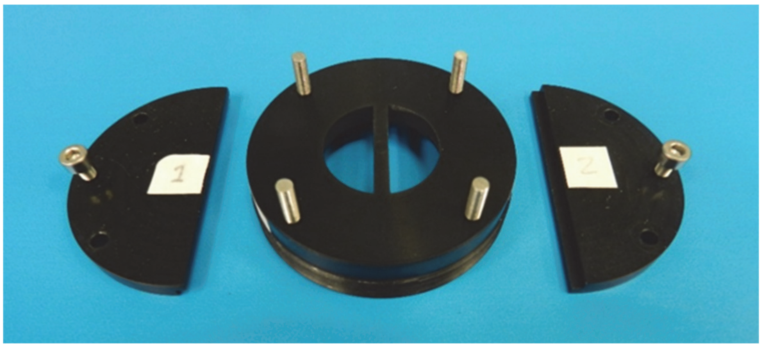

Figure 2. Lens attachment for non-linearity measurement. Zero, one or two apertures can be open.

Both non-linearity devices are double aperture devices with two removable aperture covers, designated A1 and A2. Measurements are made in sequence as follows:

i) measure the background (dark current) signal of the thermometer, $S0$

ii) remove aperture cover A1 and measure the signal $S1$

iii) remove aperture cover A2, to fully open the double aperture, and measure the signal $S1,2$

iv) place aperture cover A2 onto aperture 1 and measure the signal $S2$.

The non−linearity is then calculated from Equation 2:

$$NL = \frac{(S1 - S0) + (S2 - S0)}{S1,2 - S0} \qquad (2)$$

This sequence of measurements is repeated at different furnace temperatures to give a non−linearity assessment over as wide a range of thermometer signals as possible.

3.2.2 Size-of-source effect measurement

The size-of-source effect (SSE) was measured by the “indirect method” using an integrating sphere and a series of black anodised apertures. A Perspex plate with a small blackbody cavity, of nominally 3 mm diameter, was inserted into the exit port of the integrating sphere. For each aperture size measurements were made of the thermometer signal viewing the blackbody cavity, along with measurements when the thermometer was viewing the sphere with the Perspex plate moved slightly to give the radiation thermometer an uninterrupted view of the sphere. The SSE was determined using Equation 3:

$$SSE = \frac{\{Signal\ viewing\ blackbody\ cavity - background\ signal\}}{\{Signal\ viewing\ off\ cavity - background\ signal\}} \qquad (3)$$

3.2.3 Spectral response of the KC LP3

The spectral transmission of the 650 nm filter of the KC LP3 was characterised using a scanning monochromator calibrated using emission line sources and with a tungsten ribbon lamp as the radiance source. At each wavelength, the LP3 signal was measured both with and without the interference filter in place, the latter achieved by selecting an 'open' position of each of the two filter wheels. The ratio of the two signals provides the transmission profile for the filter, and this, along with the spectral response of the detector (taken to be that of a typical detector of the appropriate type from the manufacturer's data), is used to determine the spectral response of the thermometer. NPL-written software is then used to determine the effective wavelength, λ_{eff}, of the thermometer, which is described using two coefficients, A and B, using the following equation where T is the reference temperature in K:

$$\lambda_{eff} = A + \frac{B}{T} \tag{4}$$

The reference temperature in this case was assumed to be the temperature of the freezing point of Cu, 1357.77 K.

3.2.4 The spectral response of the Chino thermometer

Measurements of the spectral response of the Chino thermometer were made at the National Metrology Institute of Japan (NMIJ) prior to the start of the comparison.

3.2.5 Evaluation of the transfer Cu fixed point

The stability of the transfer Cu fixed point, over the duration of the comparison, was determined by comparison with the NPL Cu fixed point using the NPL LP3. A series of melt and freeze cycles of the transfer cell were initiated, and the average temperature of each melting and freezing plateau was determined using the NPL LP3, whose calibration had been checked using the NPL Cu fixed point. These measurements were carried out during each set of pilot measurements, except for the last set during January 2020 when the transfer Cu cell was not used, as described in Section 3.1.1.

4 RESULTS OF THE MEASUREMENTS, SEPTEMBER TO OCTOBER 2014

4.1 KEY COMPARISON RADIATION THERMOMETERS

4.1.1 Check of the KC thermometers with the transfer Cu fixed point

The results of the Cu checks carried out at the start and end of the NPL measurement campaign, using the transfer Cu point, are given in Table 1.

Table 1 Results of the checks at the Cu fixed point

Thermometer identification	Gain/ range	Output signal[1] /V or /A	Equivalent temperature change/ °C	Ambient temperature/ °C	Thermometer internal temperature/ °C
LP3 (start)	R1	2.16887 E-10 A		21.2	29.46
LP3 (end)	R1	2.16785 E-10 A	-0.04	20.7	29.45
Chino (start)	L	0.025103 V		20.6	29.871
Chino (end)	L	0.025186 V	0.28	21.4	29.876

[1] The reported output signal is the average of the signals obtained during the central half of two freezing plateaux for each thermometer, corrected for the dark reading (background).

The reproducibility of the LP3 at the Cu point is within reasonable limits (0.05 °C). However, the Chino thermometer output signal has changed by the equivalent of almost 0.3 °C which is very significant. The change was borne out by the results of the repeat measurements during the calibration.

Table 2 gives the results of measurements of the transfer Cu fixed point, by comparison with the NPL Cu fixed point and using the NPL LP3 as the transfer thermometer. The freezing temperature of the transfer Cu cell was determined from measurements of the central part of the freezing plateau, assuming that the temperature of the NPL Cu cell was 1084.62 °C.

Table 2 - the results of the measurements of the transfer Cu cell

Date	**Run identification**	$t_{\text{transfer Cu cell}}$/ °C
14 August 2014	Freeze 1	1084.47
15 August 2014	Freeze 2	1084.47
Average of freeze measurements		**1084.47**

4.1.2 The calibration of the KC transfer LP3 thermometer

The results of the calibration of the KC LP3 are given in Table 3. The output signals have been corrected for dark reading (background). For the measurements above 2400 °C the output signals are those obtained with the neutral filter in place, i.e., the results have not been adjusted to take the filter transmission into account.

The calibration was carried out at a working distance of 750 mm to the back wall of the high temperature blackbody. The aperture size of the high temperature blackbody was 25 mm.

The uncertainties associated with the calibration of the KC LP3 are given in Table 4.

The results of the range ratio and neutral filter transmission measurements are as follows.

- LP3 range ratio, R2/R1 (measured at 1500 °C) = 1.000432
- LP3 neutral filter transmission (measured at 2400 °C) = 0.12329

Table 3 Calibration results for the KC LP3 – September 2014

Nominal temperature/ °C	ITS-90 temperature / °C	Output signal[1] / A	Range setting	ND filter	LP3 internal temperature/ °C	Ambient temperature/ °C	U (k = 2) / °C
960	960.3	4.22298E−11	R1	No	29.45	20.7	0.21
1100	1100.1	2.60876E−10	R1	No	29.45	20.8	0.28
1300	1300.1	2.01550E−09	R1	No	29.45	20.9	0.34
1500	1500.0	9.80727E-09	R2	No	29.45	21.0	0.42
1700	1700.3	3.47083E−08	R2	No	29.45	20.7	0.56
1800	1800.5	5.95881E−08	R2	No	29.45	20.8	0.63
2000	2000.3	1.52056E−07	R2	No	29.45	20.9	0.75
2200	2200.0	3.32840E−07	R2	No	29.45	21.0	0.93
2400	2400.4	6.50586E−07	R2	No	29.46	21.2	1.12
2500	2500.1	1.07930E−07	R2	Yes	29.46	21.3	1.22
2600	2600.2	1.42413E−07	R2	Yes	29.46	21.5	1.35
2800	2801.1	2.35662E−07	R2	Yes	29.46	21.6	1.52
2900	2900.7	2.95262E−07	R2	Yes	29.47	22.1	1.49
3000	2999.6	3.64380E−07	R2	Yes	29.47	22.2	1.49
1300*	1299.8	2.01028E−09	R1	No	29.47	21.7	0.34
1700*	1700.1	3.46649E−08	R2	No	29.47	21.8	0.56
2400*	2399.7	6.49210E−07	R2	No	29.46	21.4	1.12

* Repeat measurements

[1] For the measurements above 2400 °C the output signals are those obtained with the neutral filter in place, i.e., the results have not been adjusted to take into account the filter transmission.

Table 4. Uncertainties in the calibration of the KC LP3 - September 2014

Source of uncertainty	Uncertainty/ °C													
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800	2900	3000
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056	0.060	0.064
Measurement of reference fixed point	0.010	0.012	0.016	0.02	0.024	0.027	0.032	0.038	0.045	0.048	0.052	0.043	0.045	0.048
Spectral responsivity measurement	0.031	0.004	0.070	0.153	0.252	0.308	0.432	0.572	0.729	0.814	0.903	0.493	0.538	0.586
SSE measurement and correction	0.014	0.017	0.022	0.028	0.035	0.039	0.047	0.055	0.065	0.070	0.075	0.099	0.105	0.112
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.213	0.227	0.242
Drift	0.072	0.089	0.116	0.148	0.183	0.202	0.243	0.287	0.336	0.361	0.388	0.148	0.158	0.168
Ambient conditions[1]	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Gain ratios	0.027	0.034	0.045	0.057	0.071	0.078	0.094	0.111	0.129	0.139	0.15	0.123	0.131	0.14
Repeatability	0.03	0.02	0.03	0.01	0.06	0.11	0.04	0.13	0.15	0.18	0.23	0.40	0.30	0.23
HTBB window transmittance	–	–	–	–	–	–	–	–	–	–	–	–	–	–
HTBB uniformity	0.00	0.03	0.03	0.01	0.05	0.02	0.06	0.04	0.08	0.06	0.06	0.11	0.05	0.10
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.038	0.047	0.062	0.079	0.098	0.108	0.130	0.153	0.179	0.193	0.207	0.000	0.000	0.000
HTBB effective diameter/ correction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.01	0.06	0.02	0.00	0.06	0.01	0.04	0.06	0.07	0.06	0.10	0.26	0.26	0.19
Transfer device SSE	0.03	0.04	0.05	0.06	0.07	0.08	0.1	0.12	0.14	0.15	0.16	0.18	0.19	0.21
Digital voltmeter/ resolution	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
u (k = 1)/ °C	**0.11**	**0.14**	**0.17**	**0.21**	**0.28**	**0.32**	**0.37**	**0.47**	**0.56**	**0.61**	**0.67**	**0.76**	**0.74**	**0.75**
U (k = 2)/ °C	**0.21**	**0.28**	**0.34**	**0.42**	**0.56**	**0.63**	**0.75**	**0.93**	**1.12**	**1.22**	**1.35**	**1.52**	**1.49**	**1.49**

Note: the components in the first nine rows are those associated with the calibration of the NPL LP3. The remaining components are those associated with the calibration of the KC thermometer.

[1] Included in the 'repeatability' and 'spectral responsivity' components.

4.1.3 The calibration of the KC transfer Chino thermometer

The results and uncertainties of the calibration of the Chino thermometer are given in Table 5 and Table 6 respectively. The output signals have been corrected for dark reading (background). The calibration was carried out at a working distance of 700 mm to the wall of the high temperature blackbody. The aperture diameter of the blackbody is 25 mm.

The results of the Chino gain ratio measurements are: L /M = 10.0445
M /H = 9.99137

Table 5. Calibration results for the KC Chino thermometer – September 2014

Nominal temperature / °C	ITS-90 temperature / °C	Output signal / V	Gain setting	Chino internal temperature/ °C	Ambient temperature/ °C	U (k = 2)/ °C
960	960.2	0.004884	L	29.87	20.7	0.44
1100	1100.1	0.030232	L	29.87	20.7	0.48
1300	1300.1	0.233187	L	29.87	20.8	0.52
1500	1500.2	1.136419	L	29.87	20.7	0.60
1700	1700.0	4.004286	L	29.87	21.3	0.82
1800	1799.9	6.863404	L	29.87	21.3	0.81
2000	1999.7	1.744366	M	29.86	21.4	1.01
2200	2199.9	3.832734	M	29.85	21.5	1.11
2400	2400.0	7.478245	M	29.84	21.5	1.25
2500	2501.2	1.011939	H	29.84	21.3	1.36
2600	2600.4	1.332981	H	29.84	21.4	1.49
2800	2800.7	2.208773	H	29.81	21.3	1.50
2900	2900.1	2.770978	H	29.80	21.7	1.54
3000	3000.5	3.433269	H	29.79	21.9	1.69
1300*	1299.6	0.232641	L	29.87	20.7	0.52
1700*	1700.4	4.020079	L	29.87	20.8	0.82
2400*	2400.6	7.495692	M	29.85	21.0	1.25

* Repeat measurements.

Table 6. Uncertainties in the calibration of the Chino thermometer – September 2014

Source of uncertainty	Uncertainty/ °C													
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800	2900	3000
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056	0.060	0.064
Measurement of reference fixed point	0.010	0.012	0.016	0.02	0.024	0.027	0.032	0.038	0.045	0.048	0.052	0.043	0.045	0.048
Spectral responsivity measurement	0.031	0.004	0.070	0.153	0.252	0.308	0.432	0.572	0.729	0.814	0.903	0.493	0.538	0.586
SSE measurement and correction	0.014	0.017	0.022	0.028	0.035	0.039	0.047	0.055	0.065	0.070	0.075	0.099	0.105	0.112
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.213	0.227	0.242
Drift	0.072	0.089	0.116	0.148	0.183	0.202	0.243	0.287	0.336	0.361	0.388	0.148	0.158	0.168
Ambient conditions[1]	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Gain ratios	0.027	0.034	0.045	0.057	0.071	0.078	0.094	0.111	0.129	0.139	0.15	0.123	0.131	0.14
Repeatability	0.02	0.01	0.012	0.01	0.06	0.1	0.06	0.08	0.14	0.19	0.24	0.25	0.13	0.25
HTBB window transmittance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB uniformity	0.02	0.04	0.05	0.06	0.21	0.12	0.23	0.17	0.06	0.06	0.05	0.10	0.07	0.04
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.038	0.047	0.062	0.079	0.098	0.108	0.130	0.153	0.179	0.193	0.207	0.000	0.000	0.000
HTBB effective diameter/ correction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.03	0.06	0.01	0.00	0.03	0.03	0.06	0.03	0.04	0.01	0.08	0.14	0.20	0.19
Transfer device SSE	0.06	0.07	0.095	0.12	0.15	0.16	0.2	0.23	0.27	0.30	0.32	0.36	0.39	0.41
Digital voltmeter	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
u (k = 1)/ °C	**0.22**	**0.24**	**0.26**	**0.30**	**0.41**	**0.41**	**0.51**	**0.55**	**0.62**	**0.69**	**0.75**	**0.75**	**0.78**	**0.84**
U (k = 2)/ °C	**0.44**	**0.48**	**0.52**	**0.60**	**0.82**	**0.81**	**1.01**	**1.11**	**1.25**	**1.36**	**1.49**	**1.50**	**1.54**	**1.69**

Note: the components in the first nine rows are those associated with the calibration of the NPL LP3. The remaining components are those associated with the calibration of the KC thermometer.

[1] Included in the ‘repeatability’ and ‘spectral responsivity’ components.

4.2 MEASUREMENTS OF THE HTFP CELLS

Table 7 Mean point of inflection temperatures for the HTFPs

Cell	Day	Melt number[1]	Melt transition step size/ K	ITS-90 radiance temperature of poi of the melt/ °C	U (k = 2) / °C
NiC#12	Day 1	2	20	1328.24	
		3	20	1328.24	
		4	20	1328.24	
		Average day 1		**1328.24**	
NiC#12	Day 2	2	20	1328.22	
		3	20	1328.23	
		4	20	1328.23	
		Average day 2		**1328.22**	
NiC#12		**Overall average**		**1328.23**	**0.28**
6Ru1	Day 1	2	20	1953.08	
		3	20	1953.09	
		4	20	1953.09	
		Average day 1		**1953.09**	
6Ru1	Day 2	2	20	1953.00	
		3	20	1952.99	
		4	20	1953.01	
		Average day 2		**1953.00**	
6Ru1		**Overall average**		**1953.04**	**0.62**
WCC#1	Day 1	2	20	2746.93	
		3	20	2746.94	
		4	20	2746.95	
		Average day 1		**2746.94**	
WCC#1	Day 2	2	20	2746.91	
		3	20	2746.92	
		4	20	2746.93	
		Average day 2		**2746.92**	
WCC#1		**Overall average**		**2746.93**	**1.14**

[1] The first melt of each day was not included in the analysis because the preceding freeze condition was not known.

Table 8. Uncertainty in the measurements of the HTFPs

	Source of uncertainty	**Uncertainty/ °C**		
		Ni−C	Ru−C	WC−C
Uncertainty in the reference thermometer (uncertainty in ITS-90 realisation)	Reference fixed point	0.015	0.030	0.055
	Measurement of reference fixed point	0.012	0.022	0.042
	Spectral responsivity measurement	0.038	0.180	0.471
	SSE measurement and correction	0.027	0.053	0.096
	Nonlinearity	0.058	0.112	0.207
	Gain ratios	0.034	0.065	0.143
	Drift	0.041	0.078	0.086
	Ambient conditions[1]	0.000	0.000	0.000
	Repeatability[2]	-	-	-
Uncertainty in the measurements	HTBB window transmittance	N/A	N/A	N/A
	HTBB effective source diameter/ correction to reference diameter[3]	-	-	-
	Emissivity	0.015	0.026	0.00
	Alignment on HTFP aperture	0.01	0.05	0.10
	Determination of the point of inflection	0.10	0.18	0.10
	Structure effect	0.00	0.00	0.00
	Repeatability	0.01	0.01	0.01
u (k = 1)/ °C		**0.14**	**0.31**	**0.57**
U (k = 2)/ °C		**0.28**	**0.62**	**1.14**

[1,2] Included in the 'measurement of reference fixed point' and 'spectral responsivity' components in rows above and the 'repeatability' component in row below.
[3] Included in the 'SSE measurement and correction' component in row above.

4.3 RESULTS OF THE NON-LINEARITY MEASUREMENTS

Table 9 Non-linearity of the KC LP3 measured with double aperture technique

Nominal source temperature / °C	Background 1 / A	S1 / A	S2 / A	S1+2 / A	Background 2 /A	Average background /A	Linearity	Non−linearity / %
2600	−4.742052E−12	3.988529E−07	3.799329E−07	7.789768E−07	−4.756262E−12	−4.749157E−12	0.999761	0.02391
2360	−4.470058E−12	1.990448E−07	1.895039E−07	3.884345E−07	−4.494880E−12	−4.482469E−12	1.000306	−0.03055
2155	−4.440934E−12	9.813698E−08	9.341567E−08	1.915314E−07	−4.439244E−12	−4.440089E−12	1.000134	−0.01341
1980	−4.396225E−12	4.834829E−08	4.601736E−08	9.435062E−08	−4.343635E−12	−4.369930E−12	1.000206	−0.02056
1830	−4.580403E−12	2.403686E−08	2.287831E−08	4.691358E−08	−4.567343E−12	−4.573873E−12	1.000131	−0.01314
1700	−4.515494E−12	1.200993E−08	1.142946E−08	2.344015E−08	−4.504339E−12	−4.509917E−12	1.000160	−0.01599
1590	−4.553005E−12	6.216320E−09	5.914817E−09	1.212999E−08	−4.441704E−12	−4.497355E−12	1.000465	−0.04651
1490	−4.586756E−12	3.173858E−09	3.019951E−09	6.197646E−09	−4.714711E−12	−4.650734E−12	1.000131	−0.01312
1400	−4.559343E−12	1.614818E−09	1.536135E−09	3.155582E−09	−4.461356E−12	−4.510350E−12	0.999962	0.00375
1400	−8.227843E−14	1.618716E−09	1.539790E−09	3.158176E−09	−	−8.227843E−14	1.000131	−0.01305
1320	−8.115071E−14	8.364092E−10	7.954492E−10	1.631545E−09	−7.876124E−14	−7.995598E−14	1.000241	−0.02411
1245	−8.082011E−14	4.204229E−10	3.997745E−10	8.199329E−10	−7.792473E−14	−7.937242E−14	1.000419	−0.04194
1175	−8.279027E−14	2.082934E−10	1.979661E−10	4.062806E−10	−8.337459E−14	−8.308243E−14	1.000153	−0.01525
1110	−8.471662E−14	1.018102E−10	9.680475E−11	1.987680E−10	−8.301439E−14	−8.386551E−14	0.999652	0.03479
1050	−8.297317E−14	4.943576E−11	4.697005E−11	9.650255E−11	−8.435404E−14	−8.366361E−14	0.999865	0.01354
995	−8.264739E−14	2.398964E−11	2.278037E−11	4.685962E−11	−	−8.264739E−14	0.999852	0.01483
2600	−4.742052E−12	3.988529E−07	3.799329E−07	7.789768E−07	−4.756262E−12	−4.749157E−12	0.999761	0.02391
2360	−4.470058E−12	1.990448E−07	1.895039E−07	3.884345E−07	−4.494880E−12	−4.482469E−12	1.000306	−0.03055
2155	−4.440934E−12	9.813698E−08	9.341567E−08	1.915314E−07	−4.439244E−12	−4.440089E−12	1.000134	−0.01341
1980	−4.396225E−12	4.834829E−08	4.601736E−08	9.435062E−08	−4.343635E−12	−4.369930E−12	1.000206	−0.02056
1830	−4.580403E−12	2.403686E−08	2.287831E−08	4.691358E−08	−4.567343E−12	−4.573873E−12	1.000131	−0.01314
1700	−4.515494E−12	1.200993E−08	1.142946E−08	2.344015E−08	−4.504339E−12	−4.509917E−12	1.000160	−0.01599
1590	−4.553005E−12	6.216320E−09	5.914817E−09	1.212999E−08	−4.441704E−12	−4.497355E−12	1.000465	−0.04651

Table 10. Non-linearity of the KC Chino measured with double aperture technique

Gain	Nominal source temperature/ °C	S2 / V	S12 / V	S1 / V	Background / V	Linearity	Non-linearity (%)
H	2800	0.417129	0.788676	0.371535	0.000010	0.999973	−0.00275
H	2550	0.222088	0.419816	0.197691	0.000004	0.999902	−0.00983
H	2350	0.122540	0.231608	0.109065	0.000004	0.999970	−0.00295
M	2833	4.509264	8.525027	4.015224	0.000014	0.999935	−0.00649
M	2580	2.412486	4.560227	2.147603	0.000014	0.999967	−0.00333
M	2375	1.327895	2.509967	1.181931	0.000010	0.999940	−0.00601
M	2190	0.709797	1.341650	0.631764	0.000005	0.999930	−0.00704
M	2030	0.380216	0.718906	0.338546	0.000005	0.999792	−0.02076
M	1890	0.204622	0.386806	0.182168	0.000004	0.999949	−0.00508
M	1770	0.112281	0.212215	0.099935	0.000004	0.999985	−0.00145
M	2030*	0.378975	0.716360	0.337361	0.000009	0.999955	−0.00452
L	2110	5.255805	9.935205	4.678666	0.000066	0.999920	−0.00805
L	1960	2.819514	5.329618	2.509925	0.000037	0.999960	−0.00405
L	1830	1.532135	2.896022	1.363859	0.000015	0.999985	−0.00147
L	1715	0.833562	1.575704	0.742070	0.000012	0.999946	−0.00537
L	1610	0.449659	0.850001	0.400339	0.000003	0.999994	−0.00064
L	1515	0.241401	0.456348	0.214944	0.000002	0.999989	−0.00115
L	1430	0.130265	0.246256	0.115989	−0.000002	0.999997	−0.00026
L	1350	0.068786	0.130046	0.061259	−0.000001	1.000007	0.00069

* repeat measurement

4.4 SIZE-OF-SOURCE EFFECT MEASUREMENTS

Table 11. Chino thermometer SSE Run 1; background = −0.000020 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
5	0.000027	0.076175	0.000617
6	0.000043	0.076200	0.000827
7	0.000049	0.076280	0.000904
9	0.000061	0.076400	0.001060
12	0.000077	0.076410	0.001269
15	0.000083	0.076380	0.001348
18	0.000088	0.076410	0.001413
20	0.000091	0.076445	0.001452
25	0.000094	0.076440	0.001491
30	0.000097	0.076610	0.001527
40	0.000101	0.076465	0.001582
50	0.000107	0.076500	0.001660

Table 12. Chino thermometer SSE Run 2; background = −0.000020 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
5	0.000027	0.076750	0.000612
6	0.000039	0.076760	0.000768
7	0.000049	0.076760	0.000899
9	0.000062	0.076755	0.001068
12	0.000075	0.076760	0.001237
15	0.000084	0.076770	0.001354
18	0.000088	0.076780	0.001406
20	0.000090	0.076840	0.001431
25	0.000093	0.076720	0.001473
30	0.000097	0.076750	0.001524
40	0.000104	0.076640	0.001618
50	0.000109	0.076630	0.001683

Table 13. Chino thermometer SSE Run 3; background = −0.000017 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
5	0.000025	0.076345	0.000550
6	0.000039	0.076345	0.000733
7	0.000050	0.076550	0.000875
9	0.000062	0.076635	0.001031
12	0.000075	0.076600	0.001201
15	0.000083	0.076550	0.001306
18	0.000088	0.076570	0.001371
20	0.000091	0.076515	0.001411
25	0.000094	0.076470	0.001451
30	0.000096	0.076450	0.001478
40	0.000103	0.076440	0.001570
50	0.000106	0.076300	0.001612

Table 14. Average of SSE runs for the Chino thermometer

Aperture size/ mm	Average SSE	Standard deviation
5	0.000593	3.732E−05
6	0.000776	4.708E−05
7	0.000893	1.553E−05
9	0.001053	1.969E−05
12	0.001236	3.421E−05
15	0.001336	2.628E−05
18	0.001397	2.258E−05
20	0.001431	2.024E−05
25	0.001472	1.989E−05
30	0.001510	2.755E−05
40	0.001590	2.491E−05
50	0.001651	3.635E−05

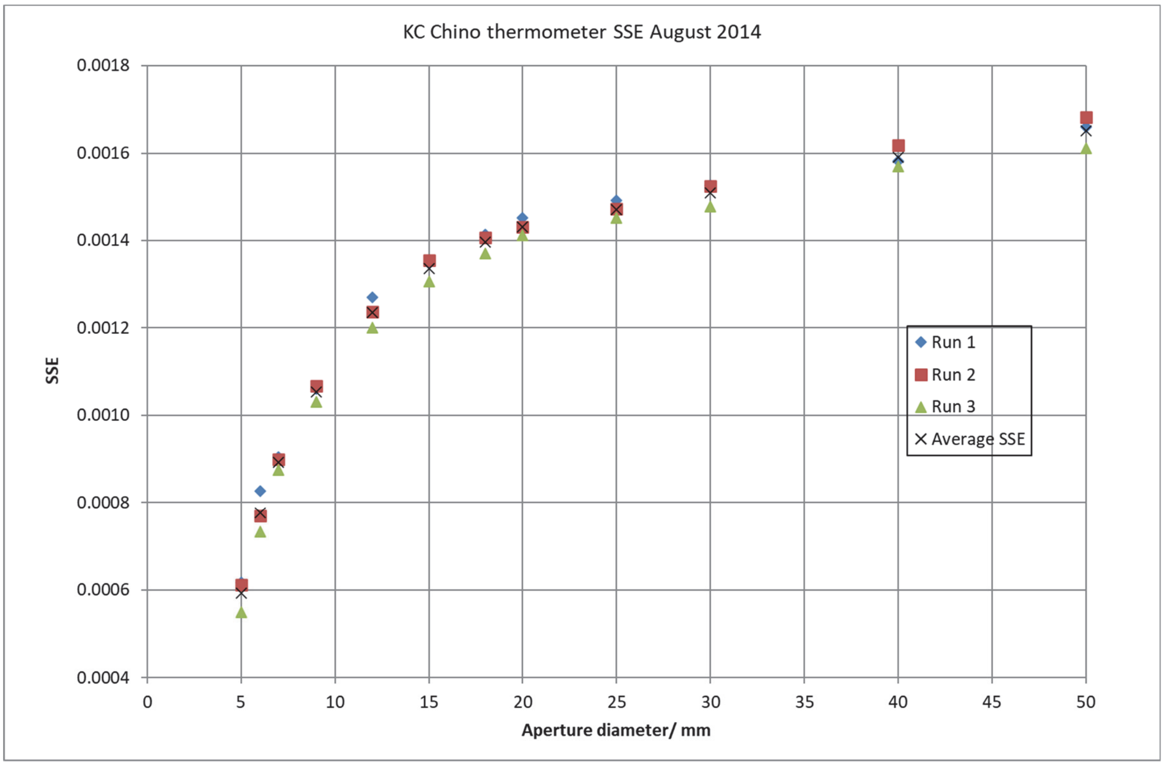

Figure 3 - the SSE of the KC Chino thermometer in August 2014

Table 15. KC LP3 SSE Run 1; background = −8.94E−14 A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
5	−1.91443E−14	7.05520E−10	0.000100
6	2.12125E−14	7.05611E−10	0.000157
7	5.27260E−14	7.03284E−10	0.000202
9	1.02560E−13	7.05507E−10	0.000272
12	1.75915E−13	7.05570E−10	0.000376
15	2.30184E−13	7.05530E−10	0.000453
18	3.15173E−13	7.06145E−10	0.000573
20	3.40997E−13	7.02131E−10	0.000613
25	4.24120E−13	7.02341E−10	0.000731
30	4.81893E−13	7.01525E−10	0.000814
40	5.98311E−13	7.04804E−10	0.000976
50	6.44866E−13	7.00473E−10	0.001048

Table 16. KC LP3 SSE Run 2; background = −8.20E−14 A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
5	−1.16118E−14	7.05378E−10	0.000100
6	2.79385E−14	7.01543E−10	0.000157
7	5.88120E−14	7.04992E−10	0.000200
9	1.16798E−13	7.02896E−10	0.000283
12	1.83838E−13	7.04452E−10	0.000377
15	2.41423E−13	7.00730E−10	0.000461
18	3.10591E−13	7.05062E−10	0.000557
20	3.52067E−13	7.04859E−10	0.000616
25	4.42946E−13	7.04621E−10	0.000745
30	4.94135E−13	7.02552E−10	0.000820
40	5.83894E−13	7.03777E−10	0.000946
50	6.52525E−13	6.99834E−10	0.001049

Table 17. KC LP3 Run 3; background = −7.83E−14 A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
5	−4.89967E−15	7.04024E−10	0.000104
6	2.45687E−14	7.04097E−10	0.000146
7	5.12699E−14	7.01381E−10	0.000185
9	1.08805E−13	7.03782E−10	0.000266
12	1.83312E−13	7.03745E−10	0.000372
15	2.65512E−13	7.02375E−10	0.000489
18	3.05809E−13	7.04067E−10	0.000546
20	3.44731E−13	7.04603E−10	0.000600
25	4.32368E−13	7.03348E−10	0.000726
30	4.94333E−13	7.03352E−10	0.000814
40	5.77798E−13	7.03249E−10	0.000933
50	6.64328E−13	7.03187E−10	0.001056

Table 18. Average of SSE runs for the LP3 thermometer

Aperture size/ mm	Average SSE	Standard deviation
5	0.000101	2.666E−06
6	0.000153	6.116E−06
7	0.000195	9.389E−06
9	0.000274	8.562E−06
12	0.000375	2.913E−06
15	0.000468	1.912E−05
18	0.000558	1.374E−05
20	0.000610	8.191E−06
25	0.000734	9.785E−06
30	0.000816	3.338E−06
40	0.000951	2.189E−05
50	0.001051	4.228E−06

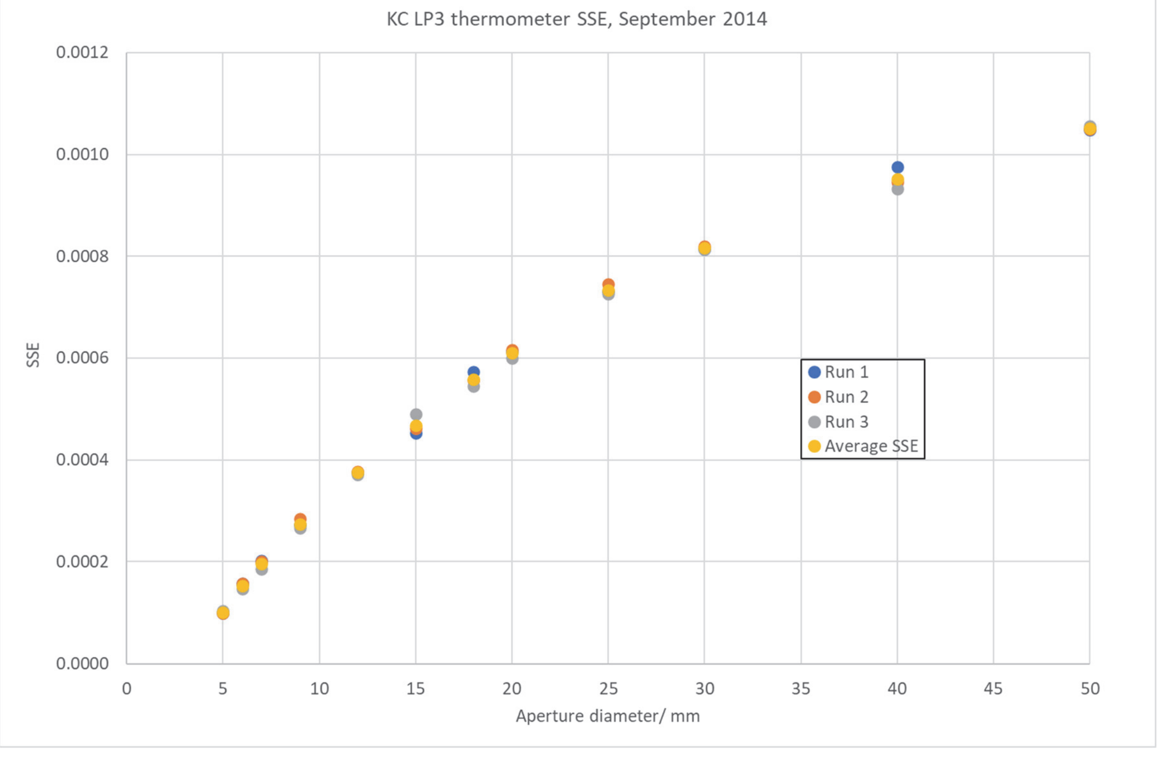

Figure 4 - the SSE of the KC LP3 in September 2014

4.5 KC LP3 FILTER CALIBRATION

Table 19. LP3 filter calibration results

Run	Scan	A coefficient	B coefficient	λ_{eff} at $T_{(Cu)}$ / nm	$t_{ambient}$/ °C
Run 1	Scan 1	651.269	537.442	651.665	21.0
	Scan 2	651.288	532.147	651.680	21.0
	Scan 3	651.286	538.398	651.683	21.0
			Average run 1	**651.676**	
Run 2	Scan 1	651.262	514.015	651.641	22.7
	Scan 2	651.255	523.098	651.640	22.7
	Scan 3	651.234	523.648	651.620	22.7
			Average run 2	**651.634**	
Run 3	Scan 1	651.241	536.82	651.636	20.8
	Scan 2	651.246	537.910	651.642	20.8
	Scan 3	651.230	537.860	651.626	20.8
			Average run 3	**651.635**	
		Average runs 1 and 3		**651.655**	
			U (k = 2)/ nm	0.16	

The effective wavelength, λ_{eff}, at the Cu fixed-point temperature is calculated from the A and B coefficients and the temperature T, in K, of the Cu point (1357.77 K) using Equation (4) above.

The measurement uncertainty is comprised of:

- the repeatability of the calibration from the standard deviation of the runs 1 and 3 results
- the calibration of the monochromator,
- the effect of using a generic detector response rather than a measured response

The temperature coefficient of the filter, taken to be the difference in λ_{eff} between the ~21 °C runs and the 22.7 °C runs is negligible, being within the repeatability of the calibration.

Table 20 - the uncertainties in the 2014 KC LP3 filter calibration

Source of uncertainty	Value / nm	Probability distribution	Divisor	u /nm
Repeatability of calibration	0.024	N	1	0.024
Temperature coefficient	0.000	R	1.732	0.000
Worst integration error	0.001	R	1.732	0.001
Detector response	0.060	R	1.732	0.035
Monochromator corrections	0.100	R	1.732	0.058
Monochromator interpolation	0.070	R	1.732	0.040
Combined uncertainty (k = 1)/ nm				0.082
Expanded uncertainty (k = 2)/ nm				0.16

5 RESULTS OF THE MEASUREMENTS, JULY TO SEPTEMBER 2015

5.1 KEY COMPARISON RADIATION THERMOMETERS

5.1.1 Check of the KC thermometers with the transfer Cu fixed point

The results of the Cu checks carried out at the start and end of the NPL measurement campaign are given in Table 21.

Table 21 Results of the checks at the Cu fixed point

Thermometer identification	Gain/ range	Output signal[1] /V or /A	Equivalent temperature change/ °C	Ambient temperature / °C	Thermometer internal temperature/ °C
LP3 (start)	R1	2.17089 E-10 A		20.9	29.46
LP3 (end)	R1	2.17374 E-10 A	0.11	20.8	29.46
Chino (start)	L	0.025262 V		20.7	2.988
Chino (end)	L	0.025281 V	0.06	20.8	2.988

[1] The reported output signal is the average of the signals obtained during the central half of two freezing plateaux for each thermometer, corrected for the dark reading (background).

On this occasion the Chino thermometer reproducibility at the Cu point is within reasonable limits (around 0.05 °C) whereas the PTB LP3 has changed by ~0.1 °C. Table 22 shows the results of the measurements of the NRC Cu point with the NPL LP3.

Table 22 Measurements of the NRC Chino Cu fixed point with the NPL LP3

Date	Run identification	$t_{\text{transfer Cu cell}}$/ °C
29 July 2015	Freeze 1	1084.52
29 July 2015	Freeze 2	1084.52
Average of freeze measurements		**1084.52**

5.1.2 The calibration of the KC transfer LP3 thermometer

The results of the calibration using the Thermo Gauge blackbody, with reference to the NPL LP3, are given in Table 23. Note that the measurements of the range ratios and neutral filter transmission were not carried out due to an oversight. The uncertainties of the calibration are given in Table 24.

Table 23 Calibration results for the KC LP3 – August 2015

Nominal temperature / °C	ITS-90 temperature / °C	Output signal[1] / A	Range setting	ND filter	LP3 internal temperature / °C	Ambient temperature/ °C	U ($k = 2$) / °C	PTB LP3 Difference 2015 – 2014/ °C
960	960.1	4.21150E-11	R1	No	29.45	20.8	0.32	-0.03
1100	1100.0	2.60891E-10	R1	No	29.45	20.7	0.35	-0.11
1300	1300.0	2.01628E-09	R1	No	29.45	20.7	0.42	-0.10
1500	1499.8	9.81045E-09	R2	No	29.46	20.8	0.50	-0.23
1700	1699.9	3.46818E-08	R2	No	29.46	20.9	0.62	-0.21
1800	1799.8	5.94555E-08	R2	No	29.46	20.9	0.70	-0.27
2000	1999.9	1.51892E-07	R2	No	29.45	20.7	0.82	-0.17
2200	2199.8	3.33227E-07	R2	No	29.45	21.0	1.03	-0.50
2400	2399.7	6.49708E-07	R2	No	29.46	21.0	1.21	-0.31
2500[2]	***2498.7***	***1.07832E-07***	**R2**	**Yes**	***29.47***	***21.9***	***1.34***	-1.08
2600[2]	***2598.8***	***1.42322E-07***	**R2**	**Yes**	***29.46***	***21.8***	***1.47***	-1.10
2800[2]	***2799.5***	***2.35600E-07***	**R2**	**Yes**	***29.47***	***21.9***	***1.32***	-1.43
2900	2899.6	2.95456E-07	R2	Yes	29.47	21.8	2.06	-1.41
3000	2999.8	3.65995E-07	R2	Yes	29.46	21.3	3.07	-1.90
960	959.9	4.19792E-11	R1	No	29.45	20.7	0.32	0.01
2200	2199.6	3.33050E-07	R2	No	29.45	21.0	1.03	-0.59
2500	2499.8	1.08217E-07	R2	Yes	29.45	21.0	1.34	-1.28
2600	2599.4	1.42607E-07	R2	Yes	29.45	21.3	1.47	-1.32
2800	2800.0	2.35827E-07	R2	Yes	29.46	21.7	1.32	-1.35
3000	2999.6	3.65967E-07	R2	Yes	29.45	21.3	3.07	0.01

* Repeat measurements

[1] the output signals have been corrected for dark reading (background). For the measurements above 2400 °C the output signals are those obtained with the neutral filter in place, i.e. the results have not been adjusted to take into account the filter transmission

[2] the numbers in bold italics (2500 °C, 2600 °C and 2800 °C) are the results after the measurements at 3000 °C, which resulted in degradation of the furnace tube and very poor temperature gradients

Table 24. Uncertainties in the calibration of the KC LP3 – August 2015

Source of uncertainty	Uncertainty/ °C													
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800	2900	3000
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056	0.060	0.064
Measurement of reference fixed point	0.010	0.012	0.016	0.02	0.024	0.027	0.032	0.038	0.045	0.048	0.052	0.043	0.045	0.048
Spectral responsivity measurement	0.012	0.002	0.027	0.058	0.096	0.117	0.165	0.218	0.278	0.31	0.344	0.389	0.425	0.462
SSE measurement and correction	0.054	0.065	0.085	0.108	0.134	0.148	0.178	0.211	0.246	0.265	0.284	0.283	0.302	0.321
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.213	0.227	0.242
Drift	0.028	0.035	0.047	0.059	0.073	0.081	0.097	0.115	0.134	0.145	0.155	0.089	0.095	0.101
Ambient conditions[1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gain ratios	0.027	0.034	0.045	0.057	0.071	0.078	0.094	0.111	0.129	0.139	0.15	0.123	0.131	0.14
Repeatability	0.011	0.029	0.049	0.046	0.098	0.148	0.144	0.235	0.261	0.298	0.361	0.282	0.116	1.306
HTBB window transmittance	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HTBB uniformity	0.023	0.009	0.012	0.031	0.028	0.009	0.038	0.027	0.090	0.145	0.117	0.060	0.806	0.429
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.038	0.047	0.062	0.079	0.098	0.108	0.130	0.153	0.179	0.193	0.207	0.00	0.00	0.00
HTBB effective diameter/ correction	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.003	0.003	0.001	0.002	0.001	0.002	0.002	0.006	0.003	0.005	0.006	0.010	0.014	0.022
Transfer device SSE	0.029	0.036	0.047	0.060	0.075	0.082	0.099	0.117	0.137	0.147	0.158	0.181	0.193	0.205
Digital voltmeter/ resolution	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127
u (k = 1)/ °C	**0.16**	**0.18**	**0.21**	**0.25**	**0.31**	**0.35**	**0.41**	**0.51**	**0.61**	**0.67**	**0.74**	**0.66**	**1.03**	**1.54**
U (k = 2)/ °C	**0.32**	**0.35**	**0.42**	**0.50**	**0.62**	**0.70**	**0.82**	**1.03**	**1.21**	**1.34**	**1.47**	**1.32**	**2.06**	**3.07**

Note: the components in the first nine rows are those associated with the calibration of the NPL LP3. The remaining components are those associated with the calibration of the KC thermometer.

[1] Included in the 'repeatability' and 'spectral responsivity' components.

5.1.3 The calibration of the KC transfer Chino thermometer

The calibration results and calibration uncertainties are given in Table 25 and Table 26 respectively.

Results of the Chino gain ratio measurements: L /M = 10.04712
M /H = 9.99104

Table 25. Calibration results for the KC Chino – August 2015

Nominal temperature / °C	ITS-90 temperature / °C	Output signal[1] / V	Gain setting	Chino internal temperature/ °C	Ambient temperature/ °C	U (k = 2) / °C	Chino Difference 2015 – 2014/ °C
960	960.1	0.004898	L	29.88	20.8	0.54	-0.33
1100	1100.0	0.030325	L	29.88	20.7	0.56	-0.34
1300	1300.0	0.234278	L	29.88	20.7	0.62	-0.61
1500	1499.8	1.139356	L	29.88	20.8	0.68	-0.73
1700	1699.9	4.026248	L	29.87	20.9	0.79	-1.06
1800	1799.8	6.902311	L	29.87	20.9	0.87	-1.22
2000	1999.7	1.756373	M	29.86	20.7	0.99	-1.58
2200	2199.8	3.847725	M	29.85	21.0	1.15	-1.25
2400	2399.5	7.500751	M	29.84	21.0	1.37	-1.43
2500	2499.6	1.012343	H	29.83	21.0	1.50	-1.76
2600	2599.3	1.335029	H	29.82	21.3	1.61	-1.64
2800	2799.7	2.208208	H	29.80	21.7	1.63	-0.88
2900	2900.3	2.765629	H	29.79	21.8	2.60	1.01
3000	3000.7	3.431834	H	29.76	21.3	2.81	0.41
960	960.0	0.004891	L	29.88	20.7	0.54	0.33
2200	2199.6	3.835368	M	29.86	21.0	1.71[2]	0.56
3000	2999.7	3.418574	H	29.76	21.3	3.00[2]	-1.28

* Repeat measurements
[1] the output signals have been corrected for dark reading (background)
[2] the higher uncertainties are due to poorer thermal uniformity of the high temperature furnace

Table 26. Uncertainties in the calibration of the Chino thermometer – August 2015

Source of uncertainty	Uncertainty/ °C													
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800	2900	3000
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056	0.060	0.064
Measurement of reference fixed point	0.010	0.012	0.016	0.02	0.024	0.027	0.032	0.038	0.045	0.048	0.052	0.043	0.045	0.048
Spectral responsivity measurement	0.012	0.002	0.027	0.058	0.096	0.117	0.165	0.218	0.278	0.310	0.344	0.389	0.425	0.462
SSE measurement and correction	0.054	0.065	0.085	0.108	0.134	0.148	0.178	0.211	0.246	0.265	0.284	0.283	0.302	0.321
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.213	0.227	0.242
Drift	0.028	0.035	0.047	0.059	0.073	0.081	0.097	0.115	0.134	0.145	0.155	0.089	0.095	0.101
Ambient conditions[1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gain ratios	0.010	0.012	0.016	0.02	0.024	0.027	0.032	0.038	0.045	0.048	0.052	0.043	0.045	0.048
Repeatability	0.018	0.028	0.053	0.046	0.100	0.148	0.147	0.197	0.269	0.302	0.340	0.191	0.576	0.990
HTBB window transmittance	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HTBB uniformity	0.023	0.009	0.012	0.031	0.028	0.009	0.038	0.027	0.09	0.145	0.117	0.06	0.806	0.429
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.038	0.047	0.062	0.079	0.098	0.108	0.130	0.153	0.179	0.193	0.207	0.000	0.000	0.000
HTBB effective diameter/ correction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.003	0.001	0.002	0.001	0.002	0.001	0.001	0.003	0.003	0.002	0.001	0.004	0.011	0.020
Transfer device SSE	0.058	0.072	0.095	0.121	0.149	0.165	0.198	0.235	0.274	0.295	0.317	0.363	0.387	0.411
Digital voltmeter	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
u (k = 1)/ °C	**0.27**	**0.28**	**0.31**	**0.34**	**0.39**	**0.43**	**0.49**	**0.58**	**0.69**	**0.75**	**0.80**	**0.81**	**1.30**	**1.40**
U (k = 2)/ °C	**0.54**	**0.56**	**0.62**	**0.68**	**0.79**	**0.87**	**0.99**	**1.15**	**1.37**	**1.50**	**1.61**	**1.63**	**2.60**	**2.81**

Note: the components in the first nine rows are those associated with the calibration of the NPL LP3. The remaining components are those associated with the calibration of the KC thermometer.

[1] Included in the 'repeatability' and 'spectral responsivity' components.

5.2 MEASUREMENTS OF THE HTFP CELLS - 2015

Table 27 Mean point of inflection temperatures for the HTFPs

Cell	Day	Melt number	Melt transition step size/ K	ITS-90 radiance temperature of poi of the melt/ °C	U ($k = 2$) / °C
NiC#12	Day 1	2	20	1328.23	
		3	20	1328.23	
		4	20	1328.23	
		Average day 1		**1328.23**	
NiC#12		**Overall average**		**1328.23**	**0.31**
CoC-C	Day 1	2	20 (650 nm)	1324.82	
		3	20 (650 nm)	1324.84	
		4	20 (900 nm)	1325.12	
		5	20 (900 nm)	1325.10	
		Average day 1		**1324.97**	
	Day 2	2	20 650 nm)	1324.84	
		3	20 (650 nm)	1324.81	
		4	20 (650 nm)	1324.85	
		5	20 (650 nm)	1324.83	
		Average day 2		**1324.83**	
CoC-C		**Overall average**	**(650 nm)**	**1324.90**	**0.27**
6Ru1	Day 1	2	20	1952.92	
		3	20	1952.90	
		4	20	1952.90	
6Ru1		**Overall average**		**1952.91**	**0.63**
6Ru2	Day 1	2	20	1952.93	
		3	20	1952.94	
		4	20	1952.94	
		Average day 2		**1952.94**	
6Ru2	Day 2	2	20	1952.94	
		Average day 2		**1952.94**	
6Ru2		**Overall average**		**1952.94**	**0.63**

WCC#1	Day 1	1		2747.14	
		2	20	2747.16	
		3	20	2747.17	
		Overall average		**2747.16**	**1.11**
WCC 655C-2	Day 1	2	8	2747.33	
		3	8	2747.36	
		4	10	2747.38	
		5		2747.37	
		Average day 1		**2747.36**	
WCC 655C-2	Day 2	2	20	2747.34	
		3	20	2747.35	
		4		2747.37	
		Average day 2		**2747.36**	
WCC 655C-2		**Overall average**		**2747.36**	**1.11**

Table 28. Uncertainty in the measurements of the HTFPs – 2015

	Source of uncertainty	**Uncertainty/ °C**			
		Ni-C	Co-C	Ru-C	WC-C
Uncertainty in the reference thermometer (uncertainty in ITS-90 realisation)	Reference fixed point	0.015	0.015	0.03	0.055
	Measurement of reference fixed point	0.027	0.027	0.053	0.097
	Spectral responsivity measurement	0.029	0.029	0.142	0.372
	SSE measurement and correction	0.077	0.077	0.149	0.274
	Nonlinearity	0.058	0.058	0.112	0.207
	Gain ratios	0.033	0.033	0.065	0.119
	Drift	0.024	0.024	0.047	0.086
	Ambient conditions[1]	0	0	0	0
	Repeatability[2]	-	-	-	-
Uncertainty in the measurements	HTBB window transmittance	N/A	N/A	N/A	N/A
	HTBB effective source diameter/ correction to reference diameter[3]	-	-	-	-
	Emissivity	0.015	0.015	0.026	0
	Alignment on HTFP aperture	0.01	0.01	0.05	0.1
	Determination of the point of inflection	0.1	0.05	0.18	0.1
	Structure effect	0.00	0.01	0.00	0.00
	Repeatability	0.03	0.05	0.01	0.02
u (k = 1)/ °C		**0.15**	**0.14**	**0.32**	**0.56**
U (k = 2)/ °C		**0.31**	**0.27**	**0.63**	**1.11**

[1,2] Included in the 'measurement of reference fixed point' and 'spectral responsivity' components in rows above and the 'repeatability' component in row below.
[3] Included in the 'SSE measurement and correction' component in row above.

6 RESULTS OF THE MEASUREMENTS, SEPTEMBER TO OCTOBER 2016

6.1 KEY COMPARISON RADIATION THERMOMETERS

6.1.1 Check of the KC thermometers with the transfer Cu fixed point

The results of the Cu checks carried out at the start and end of the NPL measurement campaign are given in Table 29.

Table 29 Temperature drift at the Cu point

Thermometer identification	Gain/ range	Output signal[1] /V or /A	Equivalent temperature change/ °C	Ambient temperature / °C	Thermometer internal temperature/ °C
LP3 (start)	R1	2.17119 E-10 A		22.5	29.47
LP3 (end)	R1	2.17601 E-10 A	+0.19	20.9	29.46
Chino (start)	L	0.025290 V		22.0	2.9877
Chino (end)	L	0.025322 V	+0.11	20.4	2.9884

[1] The reported output signal is the average of the signals obtained during the central half of three freezing plateaux for each thermometer at the start and two freezing plateaux for each thermometer at the end, corrected for the dark reading (background).

On this occasion the both the Chino thermometer and PTB LP3 have changed significantly at the Cu point (more than 0.05 °C). Table 30 shows the results of the measurements of the NRC Cu point with the NPL LP3.

Table 30 Measurements of the NRC Chino Cu fixed point with the NPL LP3

Date	Run identification	Average t_{Cu} with NPL LP3/ °C
19 September 2016	Freeze 1	1084.52
19 September 2016	Freeze 2	1084.52
19 September 2016	Freeze 3	1084.52
19 September 2016	**Average**	**1084.52**

6.1.2 The calibration of the KC transfer LP3 thermometer

The results of the calibration using the Thermo Gauge blackbody, with reference to the NPL LP3, are given Table 31.

- LP3 range ratio, R2/R1 (measured at 1300 °C) = 1.000635
- LP3 neutral filter transmission (measured at 2400 °C) = 0.12384

The uncertainties of the calibration are given in Table 32.

Table 31 Calibration results for the KC LP3 – September/ October 2016

Nominal temperature/ °C	ITS-90 temperature / °C	Output signal[1] / A	Range setting	ND filter	LP3 internal temperature/ °C	Ambient temperature/ °C	U (k = 2) / °C
960	960.0	4.20982E-11	R1	No	29.48	22.5	0.31
1100	1100.1	2.61739E-10	R1	No	29.48	22.6	0.34
1300	1300.2	2.02323E-09	R1	No	29.48	22.6	0.39
1500	1500.1	9.84495E-09	R2	No	29.48	22.3	0.47
1700	1700.1	3.47810E-08	R2	No	29.48	22.8	0.59
1800	1800.3	5.97640E-08	R2	No	29.48	22.5	0.79
2000	2000.2	1.52611E-07	R2	No	29.48	22.4	0.79
2200	2200.2	3.34672E-07	R2	No	29.48	22.6	0.91
2400	2400.2	6.52660E-07	R2	No	29.48	23.0	1.07
2500	2500.1	1.08824E-07	R2	Yes	29.48	22.7	1.16
2600	2600.2	1.43624E-07	R2	Yes	29.48	22.6	1.28
2800	2800.9	2.37156E-07	R2	Yes	29.48	22.6	1.69
2900	2902.8	2.98333E-07	R2	Yes	29.48	23.0	3.29
3000	3003.5	3.69176E-07	R2	Yes	29.49	23.3	4.71
960*	960.0	4.21325E-11	R1	No	29.47	22.1	0.31
1800*	1800.0	5.96116E-08	R2	No	29.48	22.3	0.79
2600*	2600.1	1.43564E-07	R2	Yes	29.49	22.8	1.28

* Repeat measurements

[1] the output signals have been corrected for dark reading (background). For the measurements above 2400 °C the output signals are those obtained with the neutral filter in place, i.e., the results have not been adjusted to take into account the filter transmission.

Table 32. Uncertainties in the calibration of the KC LP3 – 2016

Source of uncertainty	Uncertainty/ °C													
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800	2900	3000
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056	0.060	0.064
Measurement of reference fixed point	0.029	0.036	0.047	0.059	0.073	0.081	0.097	0.115	0.135	0.145	0.155	0.100	0.107	0.114
Spectral responsivity measurement	0.012	0.002	0.027	0.058	0.096	0.117	0.165	0.218	0.278	0.310	0.344	0.389	0.425	0.462
SSE measurement and correction	0.052	0.065	0.085	0.108	0.134	0.148	0.178	0.211	0.246	0.265	0.284	0.283	0.302	0.321
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.213	0.227	0.242
Drift	0.028	0.035	0.047	0.059	0.073	0.081	0.097	0.115	0.134	0.145	0.155	0.089	0.095	0.101
Ambient conditions[1]	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Gain ratios	0.027	0.034	0.045	0.057	0.071	0.078	0.094	0.111	0.129	0.139	0.15	0.123	0.131	0.14
Repeatability	0.04	0.04	0.05	0.04	0.02	0.11	0.08	0.06	0.06	0.04	0.02	0.47	1.15	1.70
HTBB window transmittance	–	–	–	–	–	–	–	–	–	–	–	–	–	–
HTBB uniformity	0.06	0.06	0.05	0.05	0.09	0.09	0.10	0.09	0.07	0.05	0.05	0.02	0.12	0.12
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.04	0.05	0.06	0.08	0.10	0.11	0.13	0.15	0.18	0.19	0.21	0.00	0.00	0.00
HTBB effective diameter/ correction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.01	0.01	0.01	0.02	0.03	0.20	0.05	0.00	0.03	0.07	0.14	0.38	0.98	1.48
Transfer device SSE	0.02	0.03	0.04	0.05	0.06	0.06	0.08	0.09	0.11	0.12	0.12	0.14	0.15	0.16
Digital voltmeter/ resolution	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
u (k = 1)/ °C	**0.16**	**0.17**	**0.20**	**0.24**	**0.29**	**0.40**	**0.40**	**0.46**	**0.54**	**0.58**	**0.64**	**0.85**	**1.64**	**2.36**
U (k = 2)/ °C	**0.31**	**0.34**	**0.39**	**0.47**	**0.59**	**0.79**	**0.79**	**0.91**	**1.07**	**1.16**	**1.28**	**1.69**	**3.29**	**4.71**

Note: the components in the first nine rows are those associated with the calibration of the NPL LP3. The remaining components are those associated with the calibration of the KC thermometer.

[1] Included in the 'repeatability' and 'spectral responsivity' components.

6.1.3 The calibration of the KC transfer Chino thermometer

The results and uncertainties of the calibration of the Chino thermometer are given in Table 33 and Table 34 respectively.

Results of the Chino gain ratio measurements: L /M = 10.0476 (± 0.0009)
M /H = 9.9870 (± 0.0031)

Table 33. Calibration results for the KC Chino thermometer – September/ October 2016

Nominal temperature / °C	ITS-90 temperature / °C	Output signal[1] / V	Gain setting	Chino internal temperature/ °C	Ambient temperature/ °C	U (k = 2) / °C
960	960.0	0.004902	L	29.88	22.5	0.52
1100	1100.1	0.030456	L	29.88	22.6	0.54
1300	1300.2	0.235210	L	29.88	22.6	0.59
1500	1500.1	1.143690	L	29.88	22.3	0.66
1700	1700.1	4.039855	L	29.88	22.8	0.77
1800	1800.3	6.941869	L	29.87	22.5	0.91
2000	2000.2	1.763965	M	29.87	22.4	0.96
2200	2200.2	3.866531	M	29.86	22.6	1.09
2400	2400.2	7.540474	M	29.84	23.0	1.26
2500	2500.1	1.016269	H	29.84	22.7	1.35
2600	2600.2	1.342371	H	29.83	22.6	1.46
2800	2800.9	2.223123	H	29.81	22.6	2.04
2900	2902.8	2.797914	H	29.80	23.0	3.41
3000	3003.5	3.465452	H	29.78	23.3	4.74
960*	960.0	0.004902	L	29.88	22.1	0.52
1800*	1800.0	6.916861	L	29.87	22.3	0.91
2600*	2600.1	1.341554	H	29.83	22.8	1.46

* Repeat measurements
[1] the output signals have been corrected for dark reading (background)

Table 34. Uncertainties in the calibration of the Chino thermometer – 2016

Source of uncertainty	Uncertainty/ °C													
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800	2900	3000
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056	0.060	0.064
Measurement of reference fixed point	0.029	0.036	0.047	0.059	0.073	0.081	0.097	0.115	0.135	0.145	0.155	0.100	0.107	0.114
Spectral responsivity measurement	0.012	0.002	0.027	0.058	0.096	0.117	0.165	0.218	0.278	0.310	0.344	0.389	0.425	0.462
SSE measurement and correction	0.052	0.065	0.085	0.108	0.134	0.148	0.178	0.211	0.246	0.265	0.284	0.283	0.302	0.321
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.213	0.227	0.242
Drift	0.028	0.035	0.047	0.059	0.073	0.081	0.097	0.115	0.134	0.145	0.155	0.089	0.095	0.101
Ambient conditions[1]	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Gain ratios	0.027	0.034	0.045	0.057	0.071	0.078	0.094	0.111	0.129	0.139	0.15	0.123	0.131	0.14
Repeatability	0.04	0.04	0.05	0.04	0.02	0.11	0.08	0.06	0.06	0.04	0.02	0.47	1.15	1.70
HTBB window transmittance	–	–	–	–	–	–	–	–	–	–	–	–	–	–
HTBB uniformity	0.06	0.06	0.05	0.05	0.09	0.09	0.10	0.09	0.07	0.05	0.05	0.02	0.12	0.12
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.04	0.05	0.06	0.08	0.10	0.11	0.13	0.15	0.18	0.19	0.21	0.00	0.00	0.00
HTBB effective diameter/ correction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.00	0.00	0.02	0.02	0.03	0.16	0.04	0.01	0.01	0.05	0.14	0.44	0.93	1.41
Transfer device SSE	0.06	0.07	0.10	0.12	0.15	0.17	0.20	0.24	0.28	0.30	0.32	0.37	0.40	0.42
Digital voltmeter	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
u (k = 1)/ °C	**0.26**	**0.27**	**0.30**	**0.33**	**0.38**	**0.45**	**0.48**	**0.55**	**0.63**	**0.67**	**0.73**	**1.02**	**1.71**	**2.37**
U (k = 2)/ °C	**0.52**	**0.54**	**0.59**	**0.66**	**0.77**	**0.91**	**0.96**	**1.09**	**1.26**	**1.35**	**1.46**	**2.04**	**3.41**	**4.74**

Note: the components in the first nine rows are those associated with the calibration of the NPL LP3. The remaining components are those associated with the calibration of the KC thermometer.

[1] Included in the 'repeatability' and 'spectral responsivity' components.

6.2 MEASUREMENTS OF THE HTFP CELLS - 2016

Table 35 Mean point of inflection temperatures for the HTFPs

Cell	Day	Melt number	Melt transition step size/ K	ITS-90 radiance temperature of poi of the melt/ °C	*U* (*k* = 2) / °C
CoC-B	Day 1	2	20 (650 nm)	1324.84	
		3	20 (650 nm)	1324.83	
		Average day 1		**1324.83**	
	Day 2	2	15 (650 nm)	1324.86	
		3	20 (650 nm)	1324.82	
		Average day 2		**1324.84**	
CoC-B		**Overall average**		**1324.84**	**0.25**
CoC-Ref	Day 1	2	20 (650 nm)	1323.88	
		3	20 (650 nm)	1323.87	
CoC-Ref		**Overall average**		**1323.88**	**0.25**
6Ru1	Day 1	2	20	1952.95[1]	
		3	20	1952.94[1]	
		Average day 1		**1952.95**	
6Ru1	Day 2	2	20	1952.92	
		3	20	1952.98	
		Average day 2		**1952.95**	
6Ru1		**Overall average**		**1952.95**	**0.64**
6Ru2	Day 1	1	20	1952.83[1]	
		2	20	1952.79[1]	
6Ru2	Day 2	2	20	1952.90	
		3		1952.90	
		Average day 2		**1952.90**	
6Ru2		**Overall average**		**1952.85**	**0.64**

[1] Poor melts possibly due to poor furnace temperature uniformity. The values have been included in the averages (note that the 6Ru2 measurements are for reference only).

WCC#1	Day 1	2		2747.04	
		3	20	2747.06	
		4	20	2747.07	
		Overall average		**2747.06**	**1.12**
WCC 655C-2	Day 1	2	20	2747.18	
		3	20	2747.22	
		4	20	2747.23	
WCC 655C-2		**Overall average**		**2747.21**	**1.12**

Table 36. Uncertainty in the measurements of the HTFPs – 2016

	Source of uncertainty	**Uncertainty/ °C**		
		Co-C	Ru-C	WC-C
Uncertainty in the reference thermometer (uncertainty in ITS-90 realisation)	Reference fixed point	0.015	0.03	0.055
	Measurement of reference fixed point	0.027	0.053	0.097
	Spectral responsivity measurement	0.029	0.142	0.372
	SSE measurement and correction	0.077	0.149	0.274
	Nonlinearity	0.058	0.112	0.207
	Gain ratios	0.033	0.065	0.119
	Drift	0.024	0.047	0.086
	Ambient conditions[1]	0	0	0
	Repeatability[2]	-	-	-
Uncertainty in the measurements	HTBB window transmittance	N/A	N/A	N/A
	HTBB effective source diameter/ correction to reference diameter[3]	-	-	-
	Emissivity	0.015	0.026	0
	Alignment on HTFP aperture	0.01	0.05	0.10
	Determination of the point of inflection	0.05	0.18	0.1
	Structure effect	0.01	0.00	0.00
	Repeatability (approximately)	0.02	0.05	0.02
u (k = 1)/ °C		**0.13**	**0.32**	**0.56**
U (k = 2)/ °C		**0.25**	**0.64**	**1.12**

[1,2] Included in the ‘measurement of reference fixed point’ and ‘spectral responsivity’ components in rows above and the ‘repeatability’ component in row below.
[3] Included in the ‘SSE measurement and correction’ component in row above.

6.3 SIZE-OF-SOURCE EFFECT MEASUREMENTS - 2016

Table 37. Chino thermometer SSE Run 1; background = 0.000003 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
3	7.7600E-06	0.06504	0.00007
5	4.4320E-05	0.06503	0.00063
6	5.4160E-05	0.06493	0.00079
7	6.0360E-05	0.06492	0.00088
9	7.3400E-05	0.06483	0.00108
12	8.4280E-05	0.06482	0.00125
15	8.8640E-05	0.06473	0.00132
20	9.9000E-05	0.06427	0.00149
25	1.0200E-04	0.06426	0.00154
30	1.0300E-04	0.06433	0.00155
40	1.0600E-04	0.06432	0.00160
50	1.1100E-04	0.06432	0.00168

Table 38. Chino thermometer SSE Run 2; background = 0.000004 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
3	7.0000E-06	0.06390	0.00005
5	4.5000E-05	0.06397	0.00064
6	5.6000E-05	0.06398	0.00081
7	6.5000E-05	0.06401	0.00095
9	7.7000E-05	0.06403	0.00114
12	8.9000E-05	0.06400	0.00133
15	9.2000E-05	0.06407	0.00137
20	1.0100E-04	0.06403	0.00152
25	1.0100E-04	0.06404	0.00151
30	1.0200E-04	0.06404	0.00153
40	1.0500E-04	0.06400	0.00158
50	1.0900E-04	0.06395	0.00164

Table 39. Chino thermometer SSE Run 3; background = 0.000004 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
3	0.000007	0.06394	0.00005
5	0.000046	0.06401	0.00066
6	0.000057	0.06403	0.00083
7	0.000064	0.06400	0.00094
9	0.000077	0.06403	0.00114
12	0.000087	0.06404	0.00130
15	0.000093	0.06404	0.00139
20	0.000098	0.06403	0.00147
25	0.000098	0.06402	0.00147
30	0.000101	0.06403	0.00152
40	0.000106	0.06397	0.00159
50	0.000107	0.06392	0.00161

Table 40. Average of SSE runs for the Chino thermometer

Aperture size/ mm	Average SSE	Standard deviation
3	0.00006	0.00002
5	0.00064	0.00001
6	0.00082	0.00002
7	0.00094	0.00004
9	0.00112	0.00003
12	0.00130	0.00003
15	0.00137	0.00003
20	0.00149	0.00002
25	0.00151	0.00004
30	0.00153	0.00002
40	0.00159	0.00001
50	0.00164	0.00003

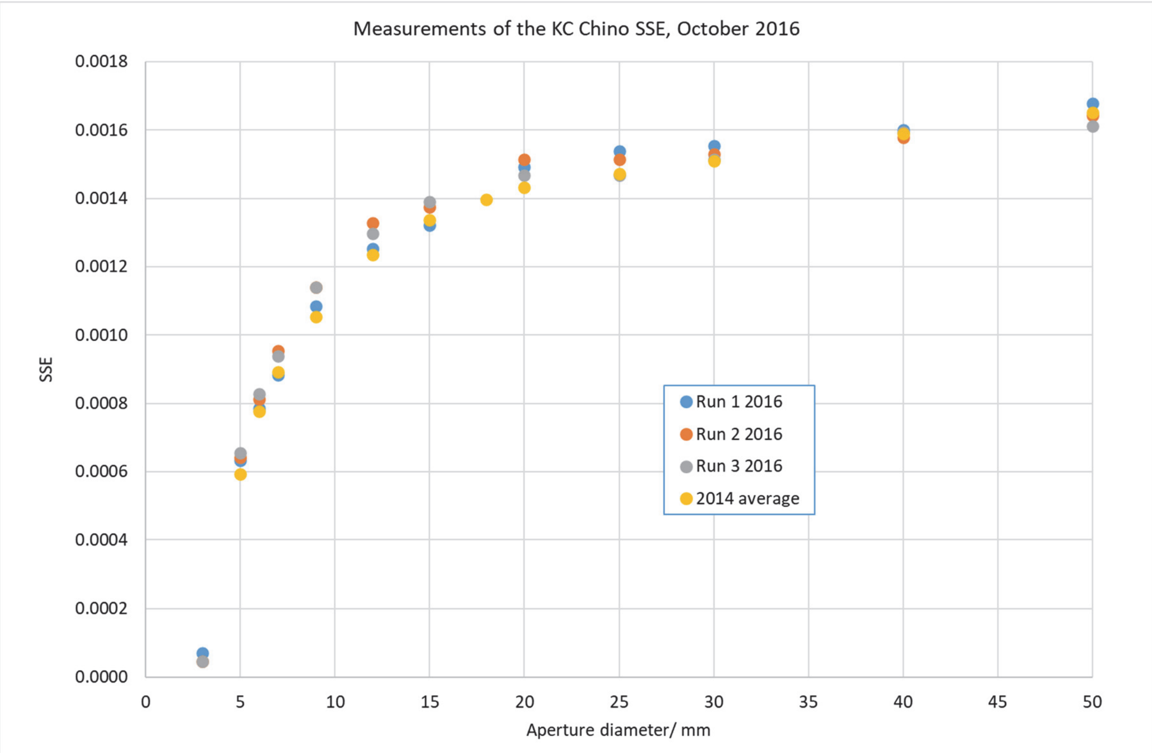

Figure 5 - comparison of Chino SSE, 2014 to 2016

Table 41. KC LP3 SSE Run 1; background = -9.164E-14 A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
3	-8.763424E-14	5.658285E-10	0.000007
5	-4.124195E-14	5.658378E-10	0.000089
6	-2.242906E-14	5.674946E-10	0.000122
7	-3.253463E-15	5.675748E-10	0.000156
9	2.974221E-14	5.674468E-10	0.000214
12	8.012445E-14	5.675301E-10	0.000303
15	1.243197E-13	5.675832E-10	0.000380
20	1.886206E-13	5.675689E-10	0.000494
25	2.358353E-13	5.674894E-10	0.000577
30	2.768476E-13	5.674009E-10	0.000649
40	3.422223E-13	5.671685E-10	0.000765
50	3.838902E-13	5.667414E-10	0.000839

Table 42. KC LP3 SSE Run 2; background = -9.138E-14 A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
3	-8.298165E-14	5.678142E-10	0.000015
5	-4.124823E-14	5.678819E-10	0.000088
6	-2.099833E-14	5.677788E-10	0.000124
7	-1.932162E-15	5.678513E-10	0.000157
9	3.410590E-14	5.678312E-10	0.000221
12	7.972075E-14	5.678794E-10	0.000301
15	1.210964E-13	5.679548E-10	0.000374
20	1.849731E-13	5.678292E-10	0.000487
25	2.350017E-13	5.678162E-10	0.000575
30	2.748973E-13	5.678031E-10	0.000645
40	3.406843E-13	5.674874E-10	0.000761
50	3.934352E-13	5.670974E-10	0.000855

Table 43. KC LP3 SSE Run 3; background = -9.517E-14 A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
3	-8.826059E-14	5.678325E-10	0.000012
5	-4.262002E-14	5.678125E-10	0.000093
6	-2.179952E-14	5.678318E-10	0.000129
7	-4.233650E-15	5.678485E-10	0.000160
9	3.188428E-14	5.677853E-10	0.000224
12	8.116172E-14	5.678412E-10	0.000310
15	1.233016E-13	5.679381E-10	0.000385
20	1.898596E-13	5.678416E-10	0.000502
25	2.351282E-13	5.677624E-10	0.000582
30	2.736024E-13	5.677058E-10	0.000649
40	3.421469E-13	5.673715E-10	0.000771
50	3.888578E-13	5.670572E-10	0.000853

Table 44. Average of SSE runs for the KC LP3 thermometer

Aperture size/ mm	Average SSE	Standard deviation
3	0.000011	0.0000039
5	0.000090	0.0000023
6	0.000125	0.0000037
7	0.000158	0.0000022
9	0.000220	0.0000051
12	0.000305	0.0000050
15	0.000380	0.0000053
20	0.000494	0.0000076
25	0.000578	0.0000035
30	0.000648	0.0000026
40	0.000766	0.0000048
50	0.000849	0.0000088

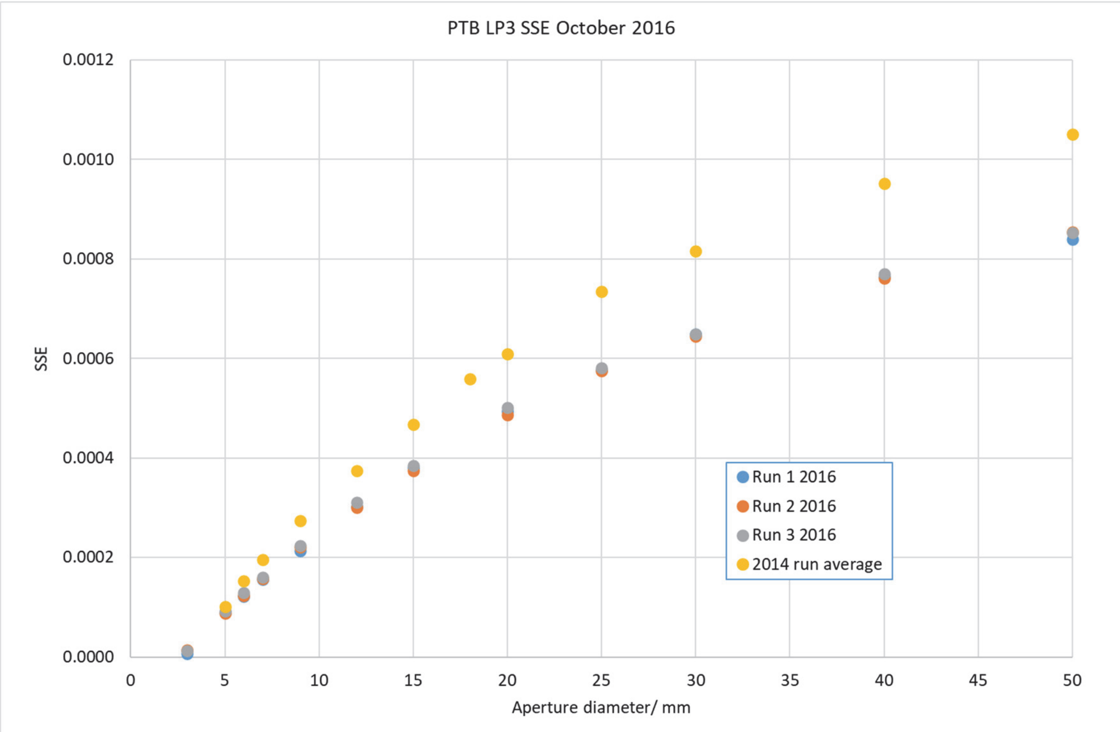

Figure 6 - comparison of KC LP3 SSE, 2014 to 2016

6.4 LP3 FILTER CALIBRATION, OCTOBER 2016

Table 45. LP3 filter calibration results, October 2016

Run	A coefficient	B coefficient	λ_{eff} at T(Cu) / nm	$t_{ambient}$/ °C
Run 1	651.308	543.443	651.708	20.0
Run 2	651.281	535.022	651.675	20.8
Run 3	651.278	526.433	651.666	20.7
	Average of 3 runs		**651.683**	
	cf. 2014 result		651.655	

Note: no significant change within the estimated uncertainty of the original calibration (0.16 nm, $k = 2$)

Table 46 - the uncertainties in the 2016 KC LP3 filter calibration

Source of uncertainty	Value / nm	Probability distribution	Divisor	u /nm
Repeatability of calibration	0.022	N	1	0.022
Temperature coefficient	0.000	R	1.732	0.000
Worst integration error	0.001	R	1.732	0.001
Detector response	0.060	R	1.732	0.035
Monochromator corrections	0.030	R	1.732	0.017
Monochromator interpolation	0.080	R	1.732	0.046
Combined uncertainty ($k = 1$)/ nm				0.064
Expanded uncertainty ($k = 2$)/ nm				0.13

7 RESULTS OF THE MEASUREMENTS, NOVEMBER 2017 TO JANUARY 2018

7.1 KEY COMPARISON RADIATION THERMOMETERS

7.1.1 Check of the KC thermometers with the transfer Cu fixed point

The results of the Cu checks carried out at the start and end of the NPL measurement campaign are given in Table 47.

Table 47 Temperature measurement at the Cu point

Thermometer identification	Gain/ range	Output signal[1] /V or /A	Equivalent temperature change/ °C	Ambient temperature / °C	Thermometer internal temperature/ °C
LP3 (start)	R1	2.18147E-10		21.8	29.47
LP3 (end)	R1	2.18237E-10	+0.04	-	29.48
Chino (start)	L	0.025323		21.6	2.9882
Chino (end)	L	0.025338	+0.05	-	2.9885

[1] The reported output signal is the average of the signals obtained during the central half of two freezing plateaux for each thermometer, corrected for the dark reading (background).

On this occasion the both the Chino thermometer and the LP3 are stable at the Cu point (within 0.05 °C).

Table 48 shows the results of the measurements of the NRC Cu point with the NPL LP3.

Table 48 Measurements of the NRC Chino Cu fixed point with the NPL LP3

Date	Run identification	Average t_{Cu} with NPL LP3/ °C
7 November 2017	Freeze 1	1084.52
7 November 2017	Freeze 2	1084.52
7 November 2017	Freeze 3	1084.51
7 November 2017	**Average**	**1084.52**

Note: results are based on the July 2017 and January 2018 Cu point calibration of the NPL LP3

7.1.2 The calibration of the KC transfer LP3 thermometer

The results of the calibration using the Thermo Gauge blackbody, with reference to the NPL LP3, are given in Table 49.

- LP3 range ratio, R2/R1 - not measured
- LP3 neutral filter transmission (measured at 2400 °C) = 0.12402

The calibration uncertainties are given in Table 50.

Table 49 Calibration results for the KC LP3 – December 2017/ January 2018

Nominal temperature/ °C	ITS-90 temperature / °C	Output signal[1] / A	Range setting	ND filter	LP3 internal temperature/ °C	Ambient temperature/ °C	U (k = 2) / °C
960	960.2	4.24039E-11	R1	No	29.47	22.1	0.46
1100	1100.2	2.62771E-10	R1	No	29.48	22.1	0.59
1300	1300.2	2.02734E-09	R1	No	29.47	22.1	0.76
1500	1500.1	9.87141E-09	R2	No	29.48	22.0	0.84
1700	1700.0	3.48148E-08	R2	No	29.48	21.9	0.99
1800	1800.3	5.97901E-08	R2	No	29.48	22.1	1.10
2000	2000.3	1.52720E-07	R2	No	29.48	22.1	1.25
2200	2200.4	3.35018E-07	R2	No	29.48	22.1	1.53
2400	2400.3	6.52794E-07	R2	No	29.48	22.0	1.79
2500	2500.3	1.09019E-07	R2	Yes	29.48	22.2	1.99
2600	2600.4	1.43986E-07	R2	Yes	29.48	22.2	2.13
2800	2800.6	2.37809E-07	R2	Yes	29.48	22.3	2.53
960*	960.1	4.22935E-11	R1	No	29.48	21.8	0.46
2000*	2000.3	1.52867E-07	R2	No	29.48	22.1	1.42
2600*	2600.5	1.44042E-07	R2	Yes	29.48	22.2	2.16

* Repeat measurements

[1] the output signals have been corrected for dark reading (background). For the measurements above 2400 °C the output signals are those obtained <u>with the neutral filter in place</u>, i.e,. the results have not been adjusted to take into account the filter transmission.

Table 50. Uncertainties in the calibration of the KC LP3 – December 2017/ January 2018

Source of uncertainty	Uncertainty/ °C											
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056
Measurement of reference fixed point	0.029	0.036	0.047	0.059	0.073	0.081	0.097	0.115	0.135	0.145	0.155	0.100
Spectral responsivity measurement	0.012	0.002	0.027	0.059	0.097	0.119	0.166	0.221	0.281	0.314	0.348	0.422
SSE measurement and correction	0.042	0.053	0.069	0.088	0.109	0.120	0.144	0.171	0.199	0.215	0.230	0.264
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.296
Drift	0.028	0.035	0.047	0.059	0.073	0.081	0.097	0.115	0.134	0.145	0.155	0.177
Ambient conditions[1]	–	–	–	–	–	–	–	–	–	–	–	–
Gain ratios	0.027	0.034	0.045	0.057	0.071	0.078	0.094	0.111	0.129	0.139	0.150	0.171
Repeatability	0.076	0.086	0.078	0.054	0.071	0.150	0.192	0.149	0.182	0.251	0.456	0.379
HTBB window transmittance	–	–	–	–	–	–	–	–	–	–	–	–
HTBB uniformity	0.16	0.20	0.25	0.24	0.26	0.26	0.27	0.34	0.35	0.36	0.27	0.33
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.13	0.16	0.22	0.27	0.34	0.37	0.45	0.53	0.62	0.67	0.72	0.82
HTBB effective diameter/ correction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.01	0.01	0.10	0.04	0.05	0.00	0.12	0.10	0.09	0.06	0.24	0.40
Transfer device SSE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Digital voltmeter/ resolution	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability	0.05	0.00	0.04	0.08	0.02	0.08	0.28	0.01	0.18	0.29	0.08	0.31
u (k = 1)/ °C	**0.23**	**0.29**	**0.38**	**0.42**	**0.49**	**0.55**	**0.71**	**0.76**	**0.90**	**0.99**	**1.08**	**1.27**
U (k = 2)/ °C	**0.46**	**0.59**	**0.76**	**0.84**	**0.99**	**1.10**	**1.42**	**1.53**	**1.79**	**1.99**	**2.16**	**2.53**

Note: the components in the first nine rows are those associated with the calibration of the NPL LP3. The remaining components are those associated with the calibration of the KC thermometer.

[1] Included in the 'repeatability' and 'spectral responsivity' components.

7.1.3 The calibration of the KC transfer Chino thermometer

The calibration results and calibration uncertainties for the Chino thermometer are given in Table 51 and Table 52 respectively.

Results of the Chino gain ratio measurements: L /M = 10.0506
M /H = 9.9923

Table 51. Calibration results for the KC Chino thermometer – December 2017/ January 2018

Nominal temperature / °C	ITS-90 temperature / °C	Output signal[1] / V	Gain setting	Chino internal temperature/ °C	Ambient temperature/ °C	U (k = 2) / °C
960	960.2	0.004924	L	29.89	22.1	0.50
1100	1100.2	0.030503	L	29.89	22.1	0.59
1300	1300.2	0.235387	L	29.89	22.1	0.76
1500	1500.1	1.144763	L	29.89	22.0	0.89
1700	1700.0	4.037321	L	29.88	21.9	1.02
1800	1800.3	6.932708	L	29.88	22.1	1.09
2000	2000.3	1.761622	M	29.88	22.1	1.27
2200	2200.4	3.865706	M	29.87	22.1	1.53
2400	2400.3	7.527959	M	29.85	22.0	1.90
2500	2500.3	1.014474	H	29.85	22.2	2.18
2600	2600.4	1.340251	H	29.84	22.2	2.18
2800	2800.6	2.217898	H	29.82	22.3	2.92
960*	960.1	0.004911	L	29.89	21.8	0.53
2000*	2000.3	1.762150	M	29.87	22.1	1.42
2600*	2600.5	1.340938	H	29.84	22.2	2.21

* Repeat measurements
[1] the output signals have been corrected for dark reading (background)

Table 52. Uncertainties in the calibration of the Chino thermometer – December 2017/ January 2018

Source of uncertainty	Uncertainty/ °C											
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056
Measurement of reference fixed point	0.029	0.036	0.047	0.059	0.073	0.081	0.097	0.115	0.135	0.145	0.155	0.100
Spectral responsivity measurement	0.012	0.002	0.027	0.059	0.097	0.119	0.166	0.221	0.281	0.314	0.348	0.422
SSE measurement and correction	0.042	0.053	0.069	0.088	0.109	0.120	0.144	0.171	0.199	0.215	0.230	0.264
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.296
Drift	0.028	0.035	0.047	0.059	0.073	0.081	0.097	0.115	0.134	0.145	0.155	0.177
Ambient conditions[1]	–	–	–	–	–	–	–	–	–	–	–	–
Gain ratios	0.027	0.034	0.045	0.057	0.071	0.078	0.094	0.111	0.129	0.139	0.150	0.171
Repeatability	0.076	0.086	0.078	0.054	0.071	0.150	0.192	0.149	0.182	0.251	0.456	0.379
HTBB window transmittance	–	–	–	–	–	–	–	–	–	–	–	–
HTBB uniformity	0.16	0.20	0.25	0.24	0.26	0.26	0.27	0.34	0.35	0.36	0.27	0.33
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.13	0.16	0.22	0.27	0.34	0.37	0.45	0.53	0.62	0.67	0.72	0.82
HTBB effective diameter/ correction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.04	0.01	0.01	0.02	0.05	0.01	0.24	0.09	0.11	0.06	0.27	0.40
Transfer device SSE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Digital voltmeter/ resolution	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability	0.14	0.01	0.10	0.17	0.14	0.02	0.13	0.17	0.36	0.53	0.28	0.79
u (k = 1)/ °C	**0.26**	**0.29**	**0.38**	**0.44**	**0.51**	**0.55**	**0.71**	**0.77**	**0.95**	**1.09**	**1.11**	**1.46**
U (k = 2)/ °C	**0.53**	**0.59**	**0.76**	**0.89**	**1.02**	**1.09**	**1.42**	**1.53**	**1.90**	**2.18**	**2.21**	**2.92**

Note: the components in the first nine rows are those associated with the calibration of the NPL LP3. The remaining components are those associated with the calibration of the KC thermometer.

[1] Included in the 'repeatability' and 'spectral responsivity' components.

7.2 MEASUREMENTS OF THE HTFP CELLS – 2017/ 2018

Table 53 Mean point of inflection temperatures for the HTFPs

Cell	Day	Melt number	Melt transition step size/ K	ITS-90 radiance temperature of poi of the melt/ °C	*U* (*k* = 2) / °C
CoC-B	Day 1	3	20	1324.67	
		4	10	1324.74	
		5	15	1324.70	
CoC-B		**Overall average**		**1324.70**	**0.26**
CoC-Ref	Day 1	2	15	1323.82	
		3	20	1323.81	
		4	10	1323.84	
CoC-Ref		**Overall average**		**1323.82**	**0.26**
6Ru1	Day 1	1	20 (650 nm)	1952.77	
		2	20 (650 nm)	1952.77	
		3	25 (650 nm)	1952.74	
		4	20 (900 nm)	1952.87	
6Ru1		**Overall average**		**1952.95**	**0.65**
6Ru2	Day 1	1	20 (650 nm)	1952.84	
		2	20 (650 nm)	1952.82	
		3	25 (650 nm)	1952.82	
		4	20 (900 nm)	1952.91	
6Ru2		**Overall average**		**1952.85**	**0.65**
WCC#2	Day 1	1	20	2746.02	
		2	20	2746.05	
		3	20	2745.99	
		Overall average		**2746.02**	**1.12**
WCC 655C-2	Day 1	1	15	2746.15	
		2	20	2746.21	
		3	20	2746.25	
WCC 655C-2		**Overall average**		**2746.20**	**1.12**

Table 54. Uncertainty in the measurements of the HTFPs – 2017/ 2018

	Source of uncertainty	**Uncertainty/ °C**		
		Co-C	Ru-C	WC-C
Uncertainty in the reference thermometer (uncertainty in ITS-90 realisation)	Reference fixed point	0.015	0.030	0.055
	Measurement of reference fixed point	0.027	0.053	0.097
	Spectral responsivity measurement	0.026	0.124	0.324
	SSE measurement and correction	0.081	0.155	0.287
	Nonlinearity	0.058	0.112	0.207
	Gain ratios	0.034	0.065	0.119
	Drift	0.024	0.047	0.086
	Ambient conditions[1]	0.000	0.000	0.000
	Repeatability[2]	-	-	-
Uncertainty in the measurements	HTBB window transmittance	N/A	N/A	N/A
	HTBB effective source diameter/ correction to reference diameter[3]	-	-	-
	Emissivity	0.015	0.026	0
	Alignment on HTFP aperture	0.01	0.05	0.10
	Determination of the point of inflection	0.05	0.18	0.1
	Structure effect	0.01	0.00	0.00
	Repeatability (approximately)	0.03	0.05	0.05
u (k = 1)/ °C		**0.13**	**0.33**	**0.56**
U (k = 2)/ °C		**0.26**	**0.65**	**1.12**

[1,2] Included in the 'measurement of reference fixed point' and 'spectral responsivity' components in rows above and the 'repeatability' component in row below.
[3] Included in the 'SSE measurement and correction' component in row above.

7.3 SIZE-OF-SOURCE EFFECT MEASUREMENTS – 2017

Table 55. Chino thermometer SSE Run 1; background = 0.000000 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
3	0.000007	0.083188	0.00009
5	0.000052	0.083188	0.00063
6	0.000068	0.083188	0.00082
7	0.000079	0.083188	0.00095
9	0.000094	0.083188	0.00113
12	0.000109	0.083188	0.00131
15	0.000121	0.083188	0.00145
18	0.000127	0.083188	0.00153
20	0.000128	0.083188	0.00154
25	0.000134	0.083188	0.00160
30	0.000137	0.083188	0.00165
40	0.000143	0.083188	0.00172
50	0.000149	0.083188	0.00179

Table 56. Chino thermometer SSE Run 2; background = 0.000000 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
3	0.000004	0.082958	0.00005
5	0.000046	0.082958	0.00055
6	0.000061	0.082958	0.00074
7	0.000072	0.082958	0.00087
9	0.000088	0.082958	0.00107
12	0.000103	0.082958	0.00125
15	0.000114	0.082958	0.00137
18	0.000121	0.082958	0.00146
20	0.000123	0.082958	0.00149
25	0.000129	0.082958	0.00156
30	0.000132	0.082958	0.00159
40	0.000139	0.082958	0.00167
50	0.000146	0.082958	0.00175

Table 57. Average of SSE runs for the Chino thermometer

Aperture size/ mm	Average SSE	Standard deviation
3	0.00007	0.00002
5	0.00059	0.00005
6	0.00078	0.00006
7	0.00091	0.00006
9	0.00110	0.00004
12	0.00128	0.00005
15	0.00141	0.00006
18	0.00149	0.00005
20	0.00152	0.00004
25	0.00158	0.00003
30	0.00162	0.00004
40	0.00170	0.00003
50	0.00177	0.00002

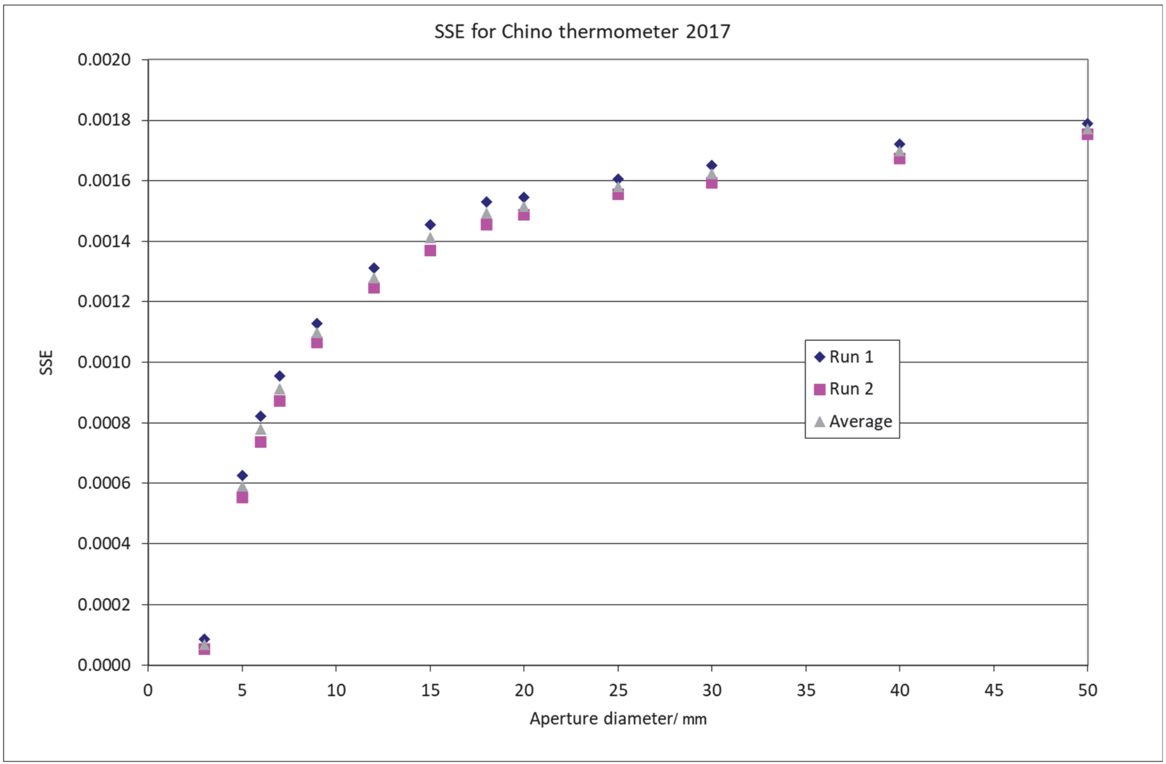

Figure 7 - the SSE of the KC Chino thermometer in 2017

Table 58. KC LP3 SSE Run 1; background = -1.03E-13A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
3	1.650E-14	6.6410E-10	0.000025
5	6.900E-14	6.6410E-10	0.000104
6	1.017E-13	6.6410E-10	0.000153
7	1.139E-13	6.6410E-10	0.000172
9	1.626E-13	6.6410E-10	0.000245
12	2.210E-13	6.6410E-10	0.000333
15	2.760E-13	6.6410E-10	0.000416
18	3.300E-13	6.6410E-10	0.000497
20	3.640E-13	6.6410E-10	0.000548
25	4.260E-13	6.6410E-10	0.000641
30	4.800E-13	6.6410E-10	0.000723
40	5.660E-13	6.6410E-10	0.000852
50	6.100E-13	6.6410E-10	0.000919

Table 59. KC LP3 SSE Run 2; background = -9.7405E-14 A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
3	6.91725E-15	6.6816E-10	0.000010
5	6.68624E-14	6.6816E-10	0.000100
6	9.00465E-14	6.6816E-10	0.000135
7	1.16182E-13	6.6816E-10	0.000174
9	1.59564E-13	6.6816E-10	0.000239
12	2.19828E-13	6.6816E-10	0.000329
15	2.77866E-13	6.6816E-10	0.000416
18	3.28398E-13	6.6816E-10	0.000491
20	3.56605E-13	6.6816E-10	0.000534
25	4.24350E-13	6.6816E-10	0.000635
30	4.74547E-13	6.6816E-10	0.000710
40	5.57912E-13	6.6816E-10	0.000835
50	6.19652E-13	6.6816E-10	0.000927

Table 60. Average of SSE runs for the KC LP3 thermometer 2017

Aperture size/ mm	Average SSE	Standard deviation
3	0.000018	0.000010
5	0.000102	0.000003
6	0.000144	0.000013
7	0.000173	0.000002
9	0.000242	0.000004
12	0.000331	0.000003
15	0.000416	0.000000
18	0.000494	0.000004
20	0.000541	0.000010
25	0.000638	0.000004
30	0.000717	0.000009
40	0.000844	0.000012
50	0.000923	0.000006

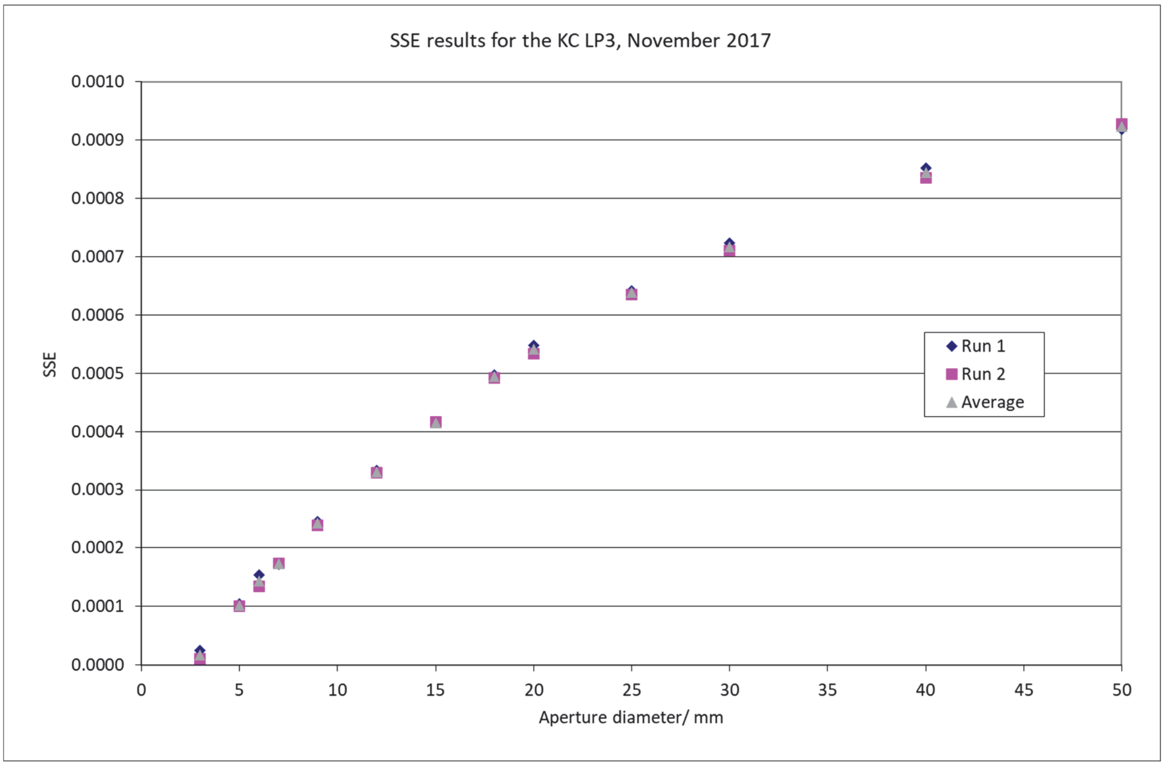

Figure 8 - The SSE of the KC LP3 thermometer in November 2017

8 RESULTS OF THE MEASUREMENTS, JANUARY 2020

8.1 KEY COMPARISON RADIATION THERMOMETERS

8.1.1 Check of the KC thermometers at the Cu fixed point

The results of the Cu checks carried out at the end of the NPL measurement campaign are given in Table 61

Table 61 Temperature measurement at the Cu point

Thermometer identification	Gain/ range	Output signal[1] /V or /A	Ambient temperature / °C	Thermometer internal temperature/ °C
LP3 (end)	R1	2.18888E-10	21.9	29.48
Chino (end)	L	0.025388	22.1	2.9889

[1] The reported output signal is the average of the signals obtained during the central half of two freezing plateaux for each thermometer, corrected for the dark reading (background).

Note: due to technical reasons the measurements were carried out using the NPL Cu point. The difference between the NPL Cu fixed-point temperature and the transfer Cu fixed-point temperature is approximately 0.1 °C (see Table 62).

Table 62 Measurements of the transfer Cu point by comparison with the NPL Cu point

Date	Average t_{Cu} with NPL LP3/ °C
August 2014	1084.47
July 2015	1084.52
September 2016	1084.52
November 2017	1084.52
Average $t_{NRC\ Cu}$	**1084.51**
Difference (NPL Cu – NRC Cu)	0.11

8.1.2 The calibration of the KC transfer LP3 thermometer

The results of the calibration using the Thermo Gauge blackbody, with reference to the NPL LP3, are given in Table 63.

- LP3 range ratio, R2/R1 (measured at 1300 °C) = 1.000530
- LP3 neutral filter transmission (measured at 2400 °C) = 0.12435

The calibration uncertainties are given in Table 64.

Table 63 Calibration results for the KC LP3 – January 2020

Nominal temperature/ °C	ITS-90 temperature / °C	Output signal[1] / A	Range setting	ND filter	LP3 internal temperature/ °C	Ambient temperature/ °C	U (k = 2) / °C
960	960.4	4.28036E-11	R1	No	29.47	22.3	0.27
1100	1100.1	2.64528E-10	R1	No	29.47	22.5	0.34
1300	1300.3	2.04503E-09	R1	No	29.48	22.6	0.48
1500	1499.7	9.91598E-09	R2	No	29.48	22.6	0.59
1700	1700.3	3.51610E-08	R2	No	29.48	22.7	0.68
1800	1800.5	6.03364E-08	R2	No	29.47	22.4	0.81
2000	2000.4	1.53970E-07	R2	No	29.48	22.7	0.87
2200	2200.5	3.37643E-07	R2	No	29.48	22.8	1.01
2400	2400.7	6.58039E-07	R2	No	29.48	23.0	1.19
2500	2500.5	1.10055E-07	R2	Yes	29.49	23.4	1.30
2600	2600.8	1.45326E-07	R2	Yes	29.48	23.3	1.43
2800	2800.5	2.39826E-07	R2	Yes	29.48	23.0	1.53
2900	2900.5	3.00867E-07	R2	Yes	29.49	23.3	1.66
3000	3001.1	3.72835E-07	R2	Yes	29.49	23.6	2.13
960*	960.0	4.25683E-11	R1	No	29.47	22.4	0.27
2000*	2000.1	1.53653E-07	R2	No	29.48	22.7	0.87
2600*	2600.8	1.45303E-07	R2	Yes	29.47	22.6	1.43

* Repeat measurements
[1] the output signals have been corrected for dark reading (background). For the measurements above 2400 °C the output signals are those obtained with the neutral filter in place, i.e., the results have not been adjusted to take the filter transmission into account the filter transmission.

Table 64. Uncertainties in the calibration of the KC LP3 – 2020

Source of uncertainty	Uncertainty/ °C													
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800	2900	3000
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056	0.06	0.064
Measurement of reference fixed point	0.029	0.036	0.047	0.059	0.073	0.081	0.097	0.115	0.135	0.145	0.155	0.178	0.19	0.202
Spectral responsivity measurement	0.012	0.002	0.027	0.058	0.096	0.117	0.165	0.218	0.278	0.31	0.344	0.417	0.455	0.496
SSE measurement and correction	0.052	0.065	0.085	0.108	0.134	0.148	0.178	0.211	0.246	0.265	0.284	0.325	0.347	0.369
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.296	0.316	0.336
Drift	0.028	0.035	0.047	0.059	0.073	0.081	0.097	0.115	0.134	0.145	0.155	0.177	0.189	0.201
Ambient conditions[1]	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Gain ratios	0.027	0.034	0.045	0.057	0.071	0.078	0.094	0.111	0.129	0.139	0.15	0.171	0.182	0.194
Repeatability	0.03	0.01	0.01	0.03	0.09	0.14	0.11	0.16	0.21	0.25	0.33	0.28	0.33	0.69
HTBB window transmittance	–	–	–	–	–	–	–	–	–	–	–	–	–	–
HTBB uniformity	0.09	0.12	0.18	0.21	0.20	0.24	0.21	0.20	0.19	0.19	0.17	0.20	0.20	0.20
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.04	0.05	0.06	0.08	0.10	0.11	0.13	0.15	0.18	0.19	0.21	0.00	0.00	0.00
HTBB effective diameter/ correction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device SSE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Digital voltmeter/ resolution	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Repeatability	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
u (k = 1)/ °C	**0.14**	**0.17**	**0.24**	**0.30**	**0.34**	**0.41**	**0.43**	**0.50**	**0.59**	**0.65**	**0.72**	**0.76**	**0.83**	**1.06**
U (k = 2)/ °C	**0.27**	**0.34**	**0.48**	**0.59**	**0.68**	**0.81**	**0.87**	**1.01**	**1.19**	**1.30**	**1.43**	**1.53**	**1.66**	**2.13**

Note: the components in the first nine rows are those associated with the calibration of the NPL LP3. The remaining components are those associated with the calibration of the KC thermometer.

[1] Included in the ‘repeatability’ and ‘spectral responsivity’ components.

8.1.3 The calibration of the KC transfer Chino thermometer

The calibration results and calibration uncertainties for the Chino thermometer are given in Table 65 and Table 66 respectively.

Results of the Chino gain ratio measurements: L /M = 10.0507
M /H = 9.9922

Table 65. Calibration results for the KC Chino thermometer – January 2020

Nominal temperature / °C	ITS-90 temperature / °C	Output signal[1] / V	Gain setting	Chino internal temperature/ °C	Ambient temperature/ °C	U (k = 2) / °C
960	960.4	0.004944	L	29.89	22.3	0.28
1100	1100.1	0.030508	L	29.89	22.5	0.34
1300	1300.3	0.235700	L	29.89	22.6	0.48
1500	1499.7	1.141455	L	29.89	22.6	0.55
1700	1700.3	4.047421	L	29.88	22.7	0.69
1800	1800.5	6.946337	L	29.88	22.4	0.81
2000	2000.4	1.763768	M	29.87	22.7	0.85
2200	2200.5	3.869093	M	29.86	22.8	1.01
2400	2400.7	7.543550	M	29.85	23.0	1.19
2500	2500.5	1.016279	H	29.84	23.4	1.29
2600	2600.8	1.343644	H	29.85	23.3	1.45
2800	2800.5	2.225969	H	29.81	23.0	1.53
2900	2900.5	2.795163	H	29.80	23.3	1.66
3000	3001.1	3.465049	H	29.79	23.6	2.13
960*	960.0	0.004921	L	29.89	22.4	0.28
2000*	2000.1	1.760900	M	29.88	22.7	0.86
2600*	2600.8	1.343592	H	29.84	22.6	1.46

* Repeat measurements
[1] the output signals have been corrected for dark reading (background)

Table 66. Uncertainties in the calibration of the Chino thermometer – 2020

Source of uncertainty	Uncertainty/ °C													
	960	1100	1300	1500	1700	1800	2000	2200	2400	2500	2600	2800	2900	3000
Reference fixed point	0.009	0.011	0.015	0.019	0.023	0.026	0.031	0.036	0.043	0.046	0.049	0.056	0.06	0.064
Measurement of reference fixed point	0.029	0.036	0.047	0.059	0.073	0.081	0.097	0.115	0.135	0.145	0.155	0.178	0.19	0.202
Spectral responsivity measurement	0.012	0.002	0.027	0.058	0.096	0.117	0.165	0.218	0.278	0.31	0.344	0.417	0.455	0.496
SSE measurement and correction	0.052	0.065	0.085	0.108	0.134	0.148	0.178	0.211	0.246	0.265	0.284	0.325	0.347	0.369
Nonlinearity	0.048	0.059	0.078	0.099	0.122	0.135	0.162	0.192	0.224	0.241	0.259	0.296	0.316	0.336
Drift	0.028	0.035	0.047	0.059	0.073	0.081	0.097	0.115	0.134	0.145	0.155	0.177	0.189	0.201
Ambient conditions[1]	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Gain ratios	0.027	0.034	0.045	0.057	0.071	0.078	0.094	0.111	0.129	0.139	0.15	0.171	0.182	0.194
Repeatability	0.03	0.01	0.01	0.03	0.09	0.14	0.11	0.16	0.21	0.25	0.33	0.28	0.33	0.69
HTBB window transmittance	–	–	–	–	–	–	–	–	–	–	–	–	–	–
HTBB uniformity	0.09	0.12	0.18	0.18	0.21	0.24	0.34	0.19	0.19	0.17	0.20	0.20	0.20	0.20
HTBB temperature stability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTBB emissivity	0.04	0.05	0.06	0.08	0.10	0.11	0.13	0.15	0.18	0.19	0.21	0.00	0.00	0.00
HTBB effective diameter/ correction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device alignment on HTBB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device short term stability	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transfer device SSE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Digital voltmeter	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
u (k = 1)/ °C	**0.14**	**0.17**	**0.24**	**0.28**	**0.35**	**0.41**	**0.43**	**0.51**	**0.60**	**0.65**	**0.73**	**0.76**	**0.83**	**1.07**
U (k = 2)/ °C	**0.28**	**0.34**	**0.48**	**0.55**	**0.69**	**0.81**	**0.85**	**1.01**	**1.19**	**1.29**	**1.45**	**1.53**	**1.66**	**2.13**

[1] Included in the 'repeatability' and 'spectral responsivity' components.

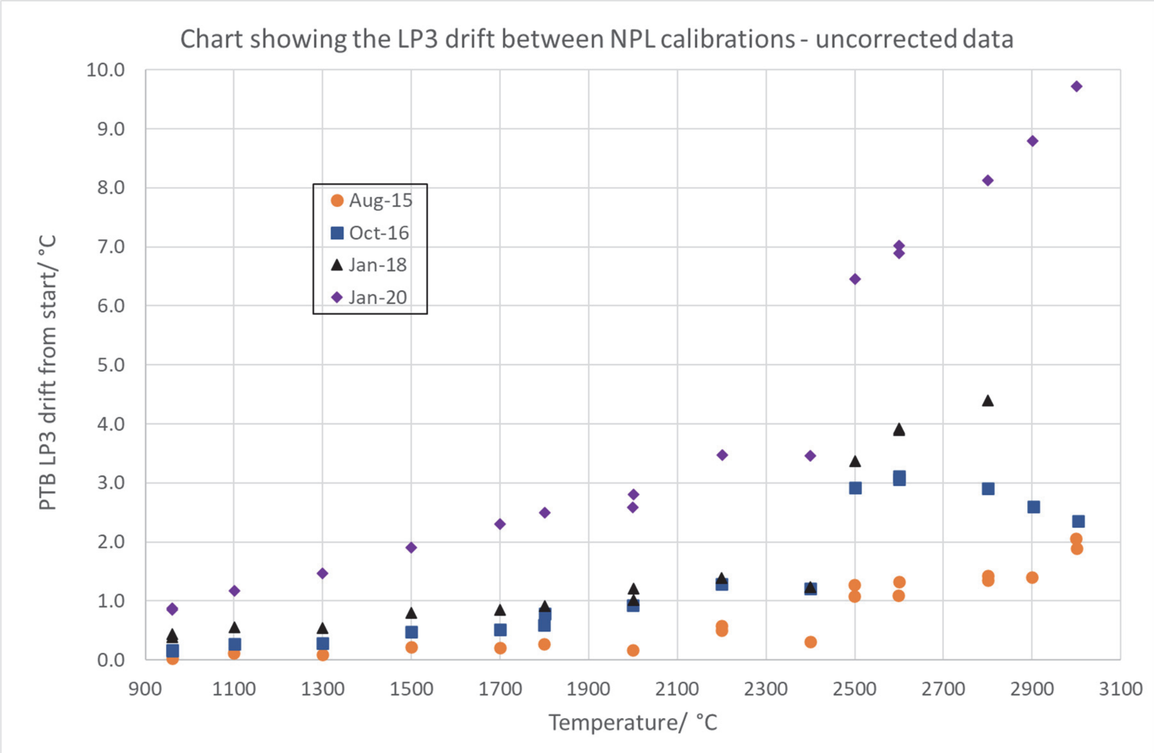

Figure 9 - the drift of the KC LP3 over the duration of the comparison

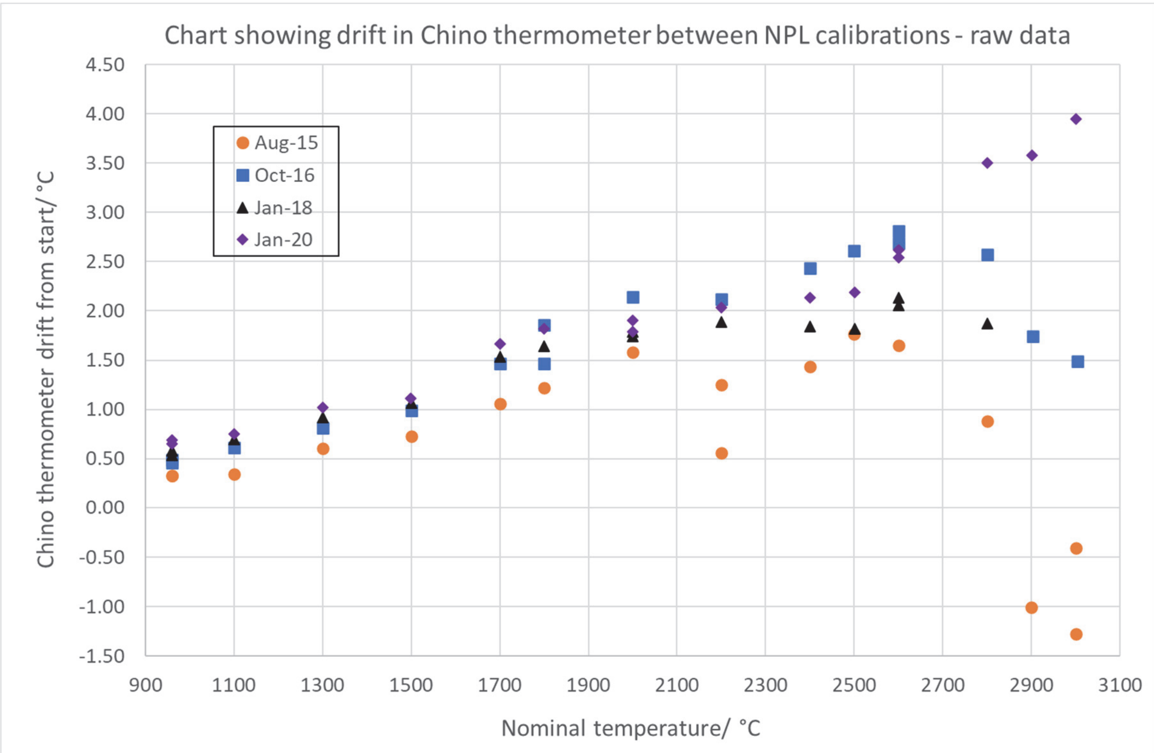

Figure 10 - the drift in the KC Chino thermometer over the duration of the comparison

8.2 MEASUREMENTS OF THE HTFP CELLS – JANUARY 2019

Table 67 Mean point of inflection temperatures for the HTFPs

Cell	Day	Melt number	Melt transition step size/ K	ITS-90 radiance temperature of poi of the melt/ °C	*U* (*k* = 2) / °C
CoC-B	Day 1	1	15 (650 nm)	1324.63	
		2	20 (650 nm)	1324.56	
		3	20 (650 nm)	1324.59	
		4	20 (900 nm)	1324.50	
		5	15 (900 nm)	1324.52	
CoC-B		**Overall average**		**1324.56**	**0.27**
6Ru1	Day 1	1	20 650 nm)	1953.04	
		2	20 (650 nm)	1953.11	
		3	25 (650 nm)	1953.12	
		4	20 (900 nm)	1953.11	
		5	20 (900 nm)	1952.90	
6Ru1		**Overall average**		**1953.06**	**0.64**

Table 68. Uncertainty in the measurements of the HTFPs – 2019

	Source of uncertainty	**Uncertainty/ °C**	
		Co-C	Ru-C
Uncertainty in the reference thermometer (uncertainty in ITS-90 realisation)	Reference fixed point	0.015	0.030
	Measurement of reference fixed point	0.027	0.053
	Spectral responsivity measurement	0.029	0.142
	SSE measurement and correction	0.077	0.149
	Nonlinearity	0.058	0.112
	Gain ratios	0.033	0.065
	Drift	0.024	0.047
	Ambient conditions[1]	0.000	0.000
	Repeatability[2]	-	-
Uncertainty in the measurements	HTBB window transmittance	N/A	N/A
	HTBB effective source diameter/ correction to reference diameter[3]	-	-
	Emissivity	0.015	0.026
	Alignment on HTFP aperture	0.01	0.05
	Determination of the point of inflection	0.05	0.18
	Structure effect	0.01	0.0
	Repeatability (approximately)	0.05	0.04
u (*k* = 1)/ °C		**0.13**	**0.32**
U (*k* = 2)/ °C		**0.27**	**0.64**

[1,2] Included in the 'measurement of reference fixed point' and 'spectral responsivity' components in rows above and the 'repeatability' component in row below.
[3] Included in the 'SSE measurement and correction' component in row above.

8.3 SIZE-OF-SOURCE EFFECT MEASUREMENTS - 2020

Table 69. Chino thermometer SSE Run 1; background = 0.000015 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
3	0.000021	0.0793	7.5676E-05
5	0.000065	0.0793	6.3064E-04
6	0.000078	0.0793	7.9460E-04
7	0.000088	0.0793	9.2073E-04
9	0.000104	0.0793	1.1225E-03
12	0.000118	0.0793	1.2991E-03
15	0.000128	0.0793	1.4252E-03
18	0.000133	0.0793	1.4883E-03
20	0.000137	0.0793	1.5388E-03
25	0.000146	0.0793	1.6523E-03
30	0.000147	0.0793	1.6649E-03
40	0.000156	0.0793	1.7784E-03
50	0.000160	0.0793	1.8288E-03

Table 70. Chino thermometer SSE Run 2; background = 0.000015 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
3	0.000018	0.0793	3.7814E-05
5	0.000062	0.0793	5.9242E-04
6	0.000078	0.0793	7.9410E-04
7	0.000087	0.0793	9.0754E-04
9	0.000103	0.0793	1.1092E-03
12	0.000118	0.0793	1.2983E-03
15	0.000128	0.0793	1.4243E-03
18	0.000133	0.0793	1.4874E-03
20	0.000135	0.0793	1.5126E-03
25	0.000141	0.0793	1.5882E-03
30	0.000147	0.0793	1.6638E-03
40	0.000152	0.0793	1.7269E-03
50	0.000156	0.0793	1.7773E-03

Table 71. Chino thermometer SSE Run 3; background = 0.000015 V

Aperture size/ mm	On spot signal / V	Off spot signal / V	SSE
3	0.000021	0.0794	7.5605E-05
5	0.000063	0.0794	6.0484E-04
6	0.000079	0.0794	8.0645E-04
7	0.000087	0.0794	9.0726E-04
9	0.000103	0.0794	1.1089E-03
12	0.000118	0.0794	1.2979E-03
15	0.000128	0.0794	1.4239E-03
18	0.000134	0.0794	1.4995E-03
20	0.000137	0.0794	1.5373E-03
25	0.000142	0.0794	1.6003E-03
30	0.000146	0.0794	1.6507E-03
40	0.000152	0.0794	1.7263E-03
50	0.000158	0.0794	1.8019E-03

Table 72. Average of SSE runs for the Chino thermometer

Aperture size/ mm	Average SSE	Standard deviation
3	6.3032E-05	2.184E-05
5	6.0930E-04	1.949E-05
6	7.9838E-04	6.991E-06
7	9.1184E-04	7.696E-06
9	1.1135E-03	7.789E-06
12	1.2984E-03	6.252E-07
15	1.4245E-03	6.859E-07
18	1.4917E-03	6.750E-06
20	1.5295E-03	1.471E-05
25	1.6136E-03	3.404E-05
30	1.6598E-03	7.898E-06
40	1.7439E-03	2.991E-05
50	1.8027E-03	2.579E-05

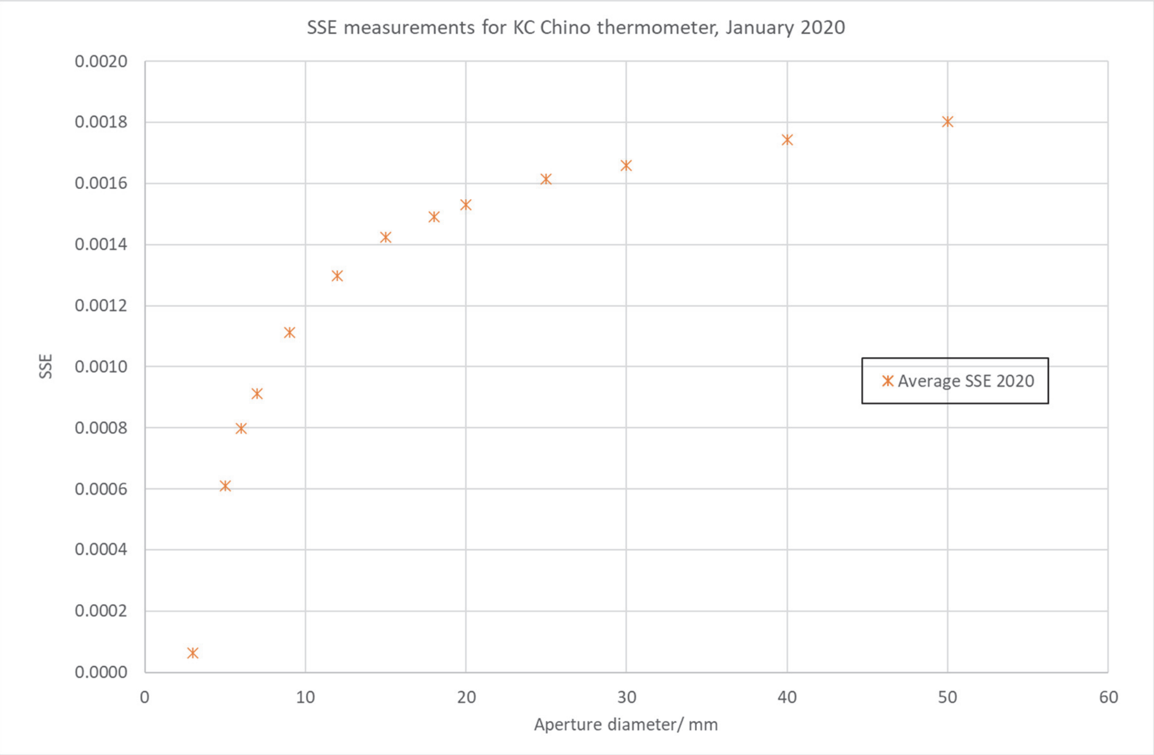

Figure 11 - the SSE of the KC Chino thermometer in January 2020

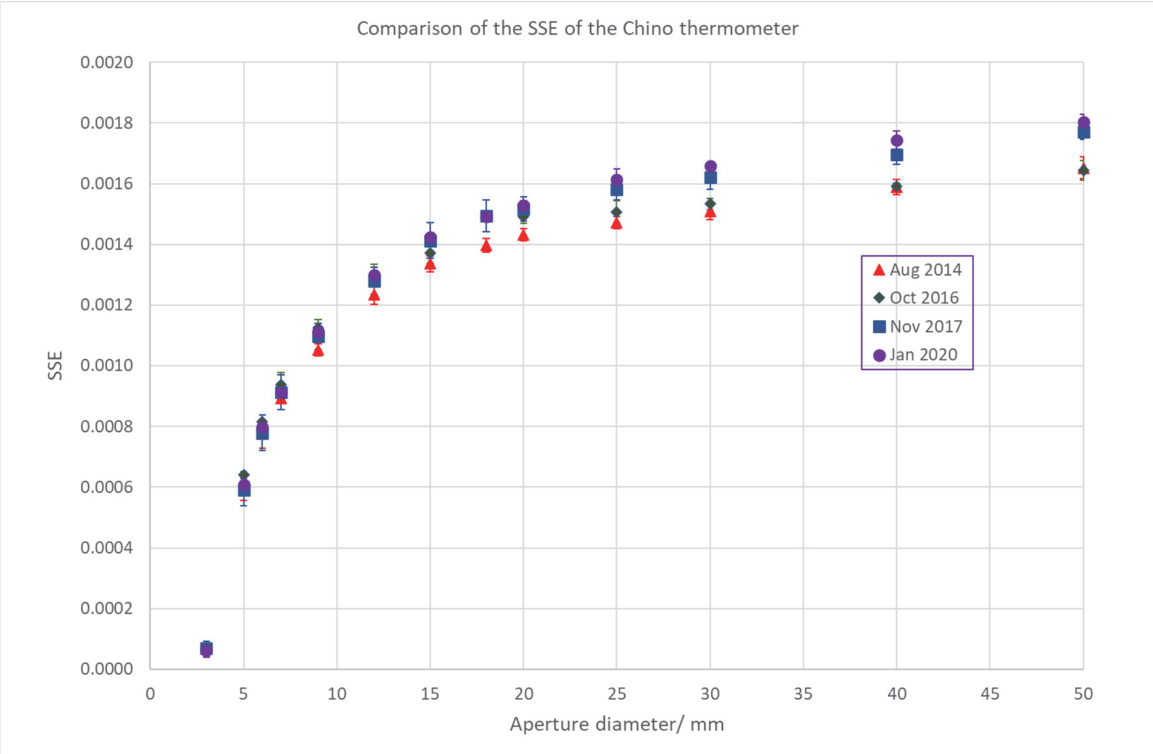

Figure 12 – comparison of the SSE results for the Chino thermometer over the duration of the comparison

Table 73. KC LP3 SSE Run 1; background = -9.3614E-14 A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
3	-7.96020E-14	6.82281E-10	2.0535E-05
5	-2.90359E-14	6.82281E-10	9.4638E-05
6	-2.80724E-15	6.82281E-10	1.3308E-04
7	2.13698E-14	6.82281E-10	1.6851E-04
9	6.53508E-14	6.82281E-10	2.3296E-04
12	1.30113E-13	6.82281E-10	3.2787E-04
15	1.93302E-13	6.82281E-10	4.2047E-04
18	2.42014E-13	6.82281E-10	4.9185E-04
20	2.74117E-13	6.82281E-10	5.3890E-04
25	3.39672E-13	6.82281E-10	6.3497E-04
30	3.87696E-13	6.82281E-10	7.0535E-04
40	4.74293E-13	6.82281E-10	8.3225E-04
50	5.34204E-13	6.82281E-10	9.2005E-04

Table 74. KC LP3 SSE Run 2; background = -9.8356E-14A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
3	-8.42576E-14	6.82891E-10	2.0643E-05
5	-3.28516E-14	6.82891E-10	9.5909E-05
6	6.31286E-16	6.82891E-10	1.4493E-04
7	1.92078E-14	6.82891E-10	1.7213E-04
9	6.03526E-14	6.82891E-10	2.3237E-04
12	1.28164E-13	6.82891E-10	3.3166E-04
15	1.90035E-13	6.82891E-10	4.2225E-04
18	2.38169E-13	6.82891E-10	4.9272E-04
20	2.73573E-13	6.82891E-10	5.4456E-04
25	3.35752E-13	6.82891E-10	6.3560E-04
30	3.86879E-13	6.82891E-10	7.1046E-04
40	4.73443E-13	6.82891E-10	8.3720E-04
50	5.35338E-13	6.82891E-10	9.2782E-04

Table 75. KC LP3 SSE Run 3; background = -9.8356E-14A

Aperture size/ mm	On spot signal / A	Off spot signal / A	SSE
3	-8.94638E-14	6.82650E-10	1.3025E-05
5	-3.06990E-14	6.82650E-10	9.9096E-05
6	-3.73141E-15	6.82650E-10	1.3859E-04
7	1.69062E-14	6.82650E-10	1.6882E-04
9	6.25993E-14	6.82650E-10	2.3575E-04
12	1.25550E-13	6.82650E-10	3.2795E-04
18	1.88280E-13	6.82650E-10	4.1983E-04
15	2.38554E-13	6.82650E-10	4.9346E-04
20	2.71174E-13	6.82650E-10	5.4124E-04
25	3.37264E-13	6.82650E-10	6.3804E-04
30	3.87944E-13	6.82650E-10	7.1227E-04
40	4.76526E-13	6.82650E-10	8.4201E-04
50	5.30815E-13	6.82650E-10	9.2153E-04

Table 76. Average of SSE runs for the KC LP3 thermometer

Aperture size/ mm	Average SSE	Standard deviation
3	1.8067E-05	4.368E-06
5	9.6547E-05	2.296E-06
6	1.3887E-04	5.933E-06
7	1.6982E-04	2.008E-06
9	2.3369E-04	1.802E-06
12	3.2916E-04	2.167E-06
15	4.2085E-04	1.255E-06
18	4.9268E-04	8.049E-07
20	5.4157E-04	2.845E-06
25	6.3620E-04	1.621E-06
30	7.0936E-04	3.590E-06
40	8.3715E-04	4.880E-06
50	9.2313E-04	4.129E-06

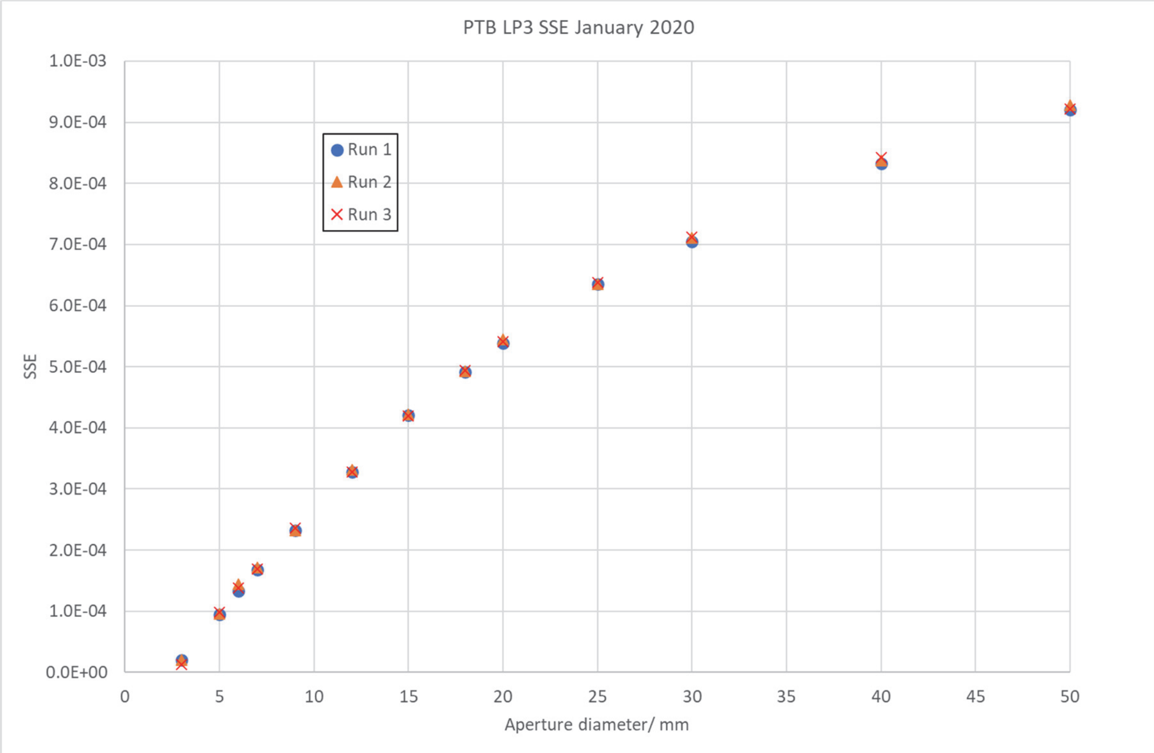

Figure 13 - the SSE of the KC LP3 thermometer in January 2020

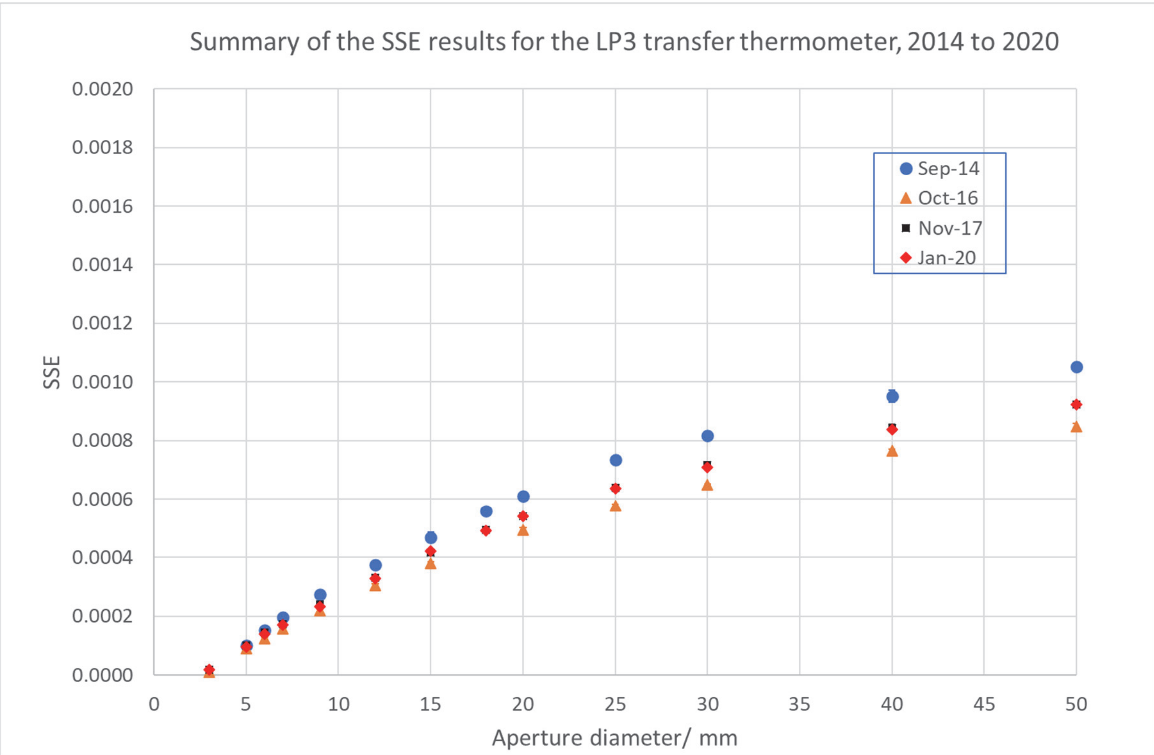

Figure 14 - comparison of the SSE results for the KC LP3 thermometer over the duration of the comparison

8.4 LP3 FILTER CALIBRATION, NOVEMBER 2019

Table 77. LP3 filter calibration results, November 2019

Run	A coefficient	B coefficient	λ_{eff} at T(Cu) / nm	$t_{ambient}$/ °C
Run 1	651.419	549.492	651.824	21.6
Run 2	651.436	533.220	651.829	21.8
Run 3	651.391	534.781	651.785	20.5
Run 4	651.407	532.245	651.799	20.5
Run 5	651.417	536.192	651.812	20.9
	Average of 3 runs		**651.810**	
	cf. 2014 result		651.655	
	cf. 2016 result		651.683	

Table 78 - the uncertainties in the 2019 KC LP3 filter calibration

Source of uncertainty	Value / nm	Probability distribution	Divisor	u /nm
Repeatability of calibration	0.018	N	1	0.018
Temperature coefficient	0.000	R	1.732	0.000
Worst integration error	0.001	R	1.732	0.001
Detector response	0.060	R	1.732	0.035
Monochromator corrections	0.050	R	1.732	0.029
Monochromator interpolation	0.030	R	1.732	0.017
Combined uncertainty (k = 1)/ nm				0.052
Expanded uncertainty (k = 2)/ nm				0.10

9 CONCLUSION

This report describes the measurements carried out by NPL during the CCT-K10 comparison. This report provides the necessary background information for the NPL results which are presented within the main CCT-K10 comparison report. Further details of the analysis methods and conclusions from the CCT-K10 comparison are given in the main report.

10 REFERENCES

[1] A comparison of the NPL and LNE-Cnam silver and copper fixed-point blackbody sources, and measurement of the silver/copper temperature interval, H C McEvoy, M Sadli, F Bourson, S Briaudeau and B Rougié, 2013, Metrologia **50** 559, https://doi.org/10.1088/0026-1394/50/6/559