National Physical Laboratory

Bilateral Comparison of Cryogenic Radiometers between NPL and UME, linked to the CCPR-S3 Supplementary Comparison

Final Report

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1. INTRODUCTION

Following the decisions of the 1994 meeting of the Consultative Committee for Photometry and Radiometry (CCPR), the BIPM acted as pilot laboratory for an international comparison of cryogenic radiometers (CCPR-S3) carried out using silicon trap detectors as transfer devices.

After the publication of the final report [1] on this comparison, the Turkish Metrology Institute UME expressed the wish to participate in a similar comparison. It was decided that NPL would organize a subsequent bilateral comparison with this laboratory, following the same general protocol as for CCPR-S3; the protocol was agreed by the CCPR WG-KC in April 2004 [2].

According to the protocol, UME was asked to calibrate a set of NPL supplied silicon trap transfer detectors at a series of laser wavelengths; a minimum of three wavelengths were to be chosen from those listed in Table 1. However due to the limited availability of suitable lasers at the laboratory, UME chose to measure at just two wavelengths: 514.5 nm and 632.8 nm.

Table 1 - Wavelengths available for the comparison

476.2 nm	Krypton laser line
488.0 nm	Argon laser line
514.5 nm	Argon laser line
568.2 nm	Krypton laser line
632.8 nm	He-Ne laser line
647.1 nm	Krypton laser line

The purpose of the bilateral comparison detailed in this report was to establish the unilateral Degrees of Equivalence (DoEs) for UME with respect to the defined Reference Value (RV) of the CCPR S3 Supplementary Comparison, using NPL as the link laboratory. This report provides the Draft B analysis of the results, following acceptance of the Pre-Draft A and Draft A reports by UME. The review of the Pre-Draft A and Draft A reports covered the following points, as laid out in the CCPR guidelines for the preparation of comparison reports:

- Review of uncertainty budgets
- Confirmation of absolute results provided by UME
- Review of relative data
- Review and approval of method to be used for analysis of results and linkage to the CCPR S3 Supplementary Comparison (as described in Section 3 of this report).

Section 4 of this report presents information on the stability of the transfer detectors and transfer uncertainty of the comparison. The results of the analysis of the absolute data are presented in Section 7. The reported results and associated uncertainties as provided by UME are given in Appendix B and NPL's uncertainties are given in Appendix A.

2. ORGANISATION

The trap detectors used in this comparison were calibrated twice at UME (in July 2004 and December 2005) and twice at NPL (in September 2005 and July 2007). The dates of the calibrations at NPL were timed to coincide with other similar comparisons.

Following completion of the measurements, but prior to preparation of the pre-draft A report, a number of staff changes took place at NPL and UME. As a consequence, analysis of the results was severely delayed and the pre-draft A report was not completed until February 2014, followed by the

Draft A report in July 2014 and (due to some communication delays) Draft B in October 2015. This final version of the report was prepared in November 2015.

3. ANALYSIS APPROACH

The purpose of the analysis is to provide unilateral Degrees of Equivalence (DoEs) for UME with respect to the defined Reference Value (RV) of the CCPR S3 Supplementary Comparison. It should be noted that NPL did not make measurements using a He-Ne laser during the CCPR Comparison; the DoE value and uncertainties from the nearest wavelength used by NPL (647.1 nm) were therefore used to determine the DoE and uncertainty for UME at 632.8 nm (see Section 7 for further discussion on this point).

The method used for analysis of the results of this bilateral comparison is as described in Appendix A of CCPR G5 'Guidelines for CCPR and RMO Bilateral Key Comparisons' prepared by the CCPR Key Comparison Working Group. According to these guidelines, the unilateral DoE of the non-link laboratory is given by:

$$D_\alpha = D_i + \left\{\left(\frac{y_\alpha}{y_i}\right) - 1\right\} \tag{1}$$

where

- D_α is the unilateral DoE of the non-link laboratory α (i.e. UME in this case)
- D_i is the unilateral DoE of the link laboratory i (i.e. NPL in this case), calculated during the CCPR S3 Supplementary Comparison
- y_α/y_i is the average value (of multiple artefacts) of the ratio between the non-link laboratory's measurement results and the link laboratory's measurement results as determined during this comparison.

The uncertainty associated with the unilateral DoE is given as an expanded uncertainty:

$$U(D_\alpha) = 2u(D_\alpha) \tag{2}$$

where the standard uncertainty $u(D_\alpha)$ is calculated using:

$$u^2(D_\alpha) = u_\alpha^2 + u^2(x_{\mathrm{ref}}) + (1 - 2w_i)s_{\mathrm{SC}}^2 + u_{i,\mathrm{r,SC}}^2 + u_{i,\mathrm{st}}^2 + u_{i,\mathrm{r,BC}}^2 + s_{\mathrm{BC}}^2 \tag{3}$$

There are four contributions in this uncertainty calculation, as described below.

- **Non-link laboratory effects**

u_α is the declared total relative standard uncertainty of the non-link laboratory for a single artefact. This includes uncertainties due to both correlated and uncorrelated effects.

- **Supplementary Comparison effects**

$u(x_{\mathrm{ref}})$ is the relative standard uncertainty associated with the S3 Supplementary Comparison Reference Value. This value is available from the CCPR S3 report (0.5×10^{-4}).

s_{SC} is the relative standard uncertainty associated with the transfer for the Supplementary Comparison. For the CCPR S3 Supplementary Comparison, this was 1×10^{-4}.

w_i is the weight assigned to the linking laboratory's measurements in the calculation of the Supplementary Comparison Reference Value. This was not given in the CCPR S3 report, so has been calculated based on the uncertainties for the participants[1].

- **Linking quality**

$u_{i,\mathrm{r,SC}}$ is the relative standard uncertainty associated with uncorrelated effects (random uncertainty) of the link laboratory during the CCPR S3 Supplementary Comparison. This was not stated in the CCPR S3 report, but is based on the random uncertainties typically achieved at NPL for the calibration of transfer trap detectors (see Table A.2).

$u_{i,\mathrm{st}}$ the relative standard uncertainty due to lack of stability of the link laboratory's scale between the Supplementary Comparison and this comparison. For NPL this is dominated by random effects associated with each measurement using the NPL trap detector calibration facility and was therefore taken to be identical to $u_{i,\mathrm{r,SC}}$ as defined above.

- **Bilateral Comparison effects**

$u_{i,\mathrm{r,BC}}$ is the relative standard uncertainty associated with uncorrelated effects (random uncertainty) of the link laboratory during this comparison. This is identical to $u_{i,\mathrm{r,SC}}$ as given above.

s_{BC} is the relative standard uncertainty associated with the transfer for this comparison, which is based on the stability of the trap detectors as determined from the NPL measurements (see Section 4).

4. STABILITY OF THE TRANSFER DETECTORS AND TRANSFER UNCERTAINTY OF THE COMPARISON

The relative change in the responsivity of the trap detectors as measured at NPL is shown in Table 2 and is consistent with the long term stability of this type of detector. The change in responsivity was small and therefore no drift correction was applied to the results. Drift effects were allowed for in the uncertainty budget through the transfer uncertainty, s_{BC}, of the comparison at each wavelength, which is calculated using Equation (4), assuming a rectangular probability distribution and using a worst case value for the change in responsivity, ΔR, at each wavelength. The transfer uncertainty calculated using this approach was slightly greater at 632.8 nm than at 514.5 nm, and the larger of these two values (i.e. 1.4×10^{-4}) was used in the analysis of results at both wavelengths.

$$s_{\mathrm{BC}} = \frac{\Delta R}{2\sqrt{3}} \qquad (4)$$

Table 2 Worst case relative change in responsivity, ΔR, for comparison trap detectors as measured by NPL (September 2005 to July 2007) and transfer uncertainty of comparison, s_{BC}.

Wavelength	Worst case relative change in responsivity as measured by NPL × 10^4	Transfer uncertainty due to relative change × 10^4
514.5 nm	3.40	0.98
632.8 nm	4.72	1.36

[1] A separate KCRV was calculated for each wavelength used in the CCPR S3 comparison, based on the weighted mean for all laboratories that made measurements at that wavelength and with no cut-off applied at any wavelength. The weighted mean at each wavelength used the values for x_i (relative difference) and u_i (uncertainty combining the standard uncertainty from each laboratory and the uncertainty associated with the transfer) summarised in Table 65 of the CCPR S3 report. The weight used for NPL for the analysis of this bilateral was therefore calculated using the uncertainties from the same Table, to ensure consistency with the CCPR S3 comparison.

5. MEASUREMENTS BY NPL

The measurement facility and procedure used by NPL were as described in the report of the CCPR S3 Supplementary Comparison [1]. The key experimental conditions, the measurement results and the associated uncertainties for NPL during this bilateral comparison, are given in Appendix A.

6. MEASUREMENTS BY UME

Details of the measurement facility and procedure used by UME, and the measurement results and associated uncertainties, are given in Appendix B.

7. RESULTS OF ANALYSIS

The results of the measurements carried out by UME have been analysed in terms of:

1. The stability of the trap detectors as measured at UME before and after transportation to NPL.
2. The internal consistency of all the trap detectors measured at UME.
3. The DoE for UME as determined by this comparison.
4. The uncertainty associated with the DoE for UME as determined by this comparison.

Point 1 was evaluated by calculating the ratios between the responsivity values assigned to each trap by UME before transportation to NPL and those assigned on their return to UME (see Table 3). Point 2 was determined by calculating the ratios between the responsivity values assigned to each trap detector by UME and the values assigned to the same trap detector by NPL, and normalising these values to the mean UME-to-NPL ratio for all the trap detectors (see Table 4). The combined uncertainties given in Table 4 are based on the information provided by UME and the uncertainty budget for NPL, and are given both including and excluding the transfer uncertainty indicated in Table 2.

Points 3 and 4 were determined as detailed in Section 3 above and the results are given in Table 5. Since NPL did not make measurements using a He-Ne laser during the CCPR S3 Comparison, the DoE and associated uncertainty from the nearest wavelength used by NPL (647.1 nm) were used to determine the DoE and associated uncertainty for UME at 632.8 nm (see footnote[2]).

Table 3 Ratio of measurements by UME before and after transportation of trap detectors to NPL.

	UME after /UME before		
Wavelength / nm	**11033T**	**11034T**	**11035T**
514.5	0.99952	0.99952	0.99952
632.8	1.00000	1.00020	0.99980

[2] The NPL DoE values and associated measurement uncertainties vary slightly with wavelength. At the wavelengths spanning 632.8 nm (i.e. 568.2 nm and 647.1 nm) the NPL DoEs are $+ 0.9 \times 10^{-4}$ and $+ 0.7 \times 10^{-4}$ respectively and the associated random uncertainties (relative standard uncertainties associated with uncorrelated effects) are 0.31×10^{-4} and 0.36×10^{-4} respectively. Analysis confirmed that the calculated value of the uncertainty associated with the DoE for UME was not significantly affected by which of these two spanning wavelengths was chosen, nor did allowing for an additional uncertainty of 0.4×10^{-4} (the difference between the two NPL DoE values) impact on the uncertainty; the standard uncertainty associated with the UME DoE value at 632.8 nm, when rounded to 2 significant figures, was 5.1×10^{-4} in each case. The choice of wavelength did, however, have a small impact on the UME DoE value at 632.8 nm. Using the NPL DoE at 647.1 nm gave a value of $- 0.3 \times 10^{-4}$ for the UME DoE at 632.8 nm, whereas using the NPL DoE at 568.2 nm gave a value of $+ 0.1 \times 10^{-4}$ for the UME DoE. This difference is small in comparison with the uncertainty associated with the DoE.

Table 4 UME-to-NPL ratio for each individual trap detector divided by mean UME-to-NPL ratio for all trap detectors.

Wavelength / nm	11033T	11034T	11035T	Combined Uncertainty (exc. transfer, *k*=1)	Combined Uncertainty (inc. transfer, *k*=1)
514.5	1.00009	1.00003	0.99988	0.00027	0.00031
632.8	1.00015	1.00000	0.99985	0.00025	0.00029

Table 5 Absolute UME-to-NPL ratio for each individual trap detector, with NPL DoEs as determined in the CCPR S3 Comparison and DoEs and associated uncertainty for UME as determined in this bilateral comparison.

Wave-length / nm	11033T	11034T	11035T	Mean UME-to-NPL ratio	$10^4 \times$ NPL DoE	$10^4 \times$ UME DoE	$10^4 \times$ Uncertainty in UME DoE
514.5	1.00189	1.00183	1.00168	1.00180	+ 0.7	+ 18.7	5.6
632.8	1.00008	0.99992	0.99977	0.99992	+ 0.5	- 0.3	5.1

8. CONCLUSIONS

Table 3 shows that the detector drift measured by UME during the course of the comparison was reasonably consistent with that measured by NPL and was sufficiently small that it was not necessary to apply a drift correction to any of the results.

Table 4 shows that the bilateral ratios (UME-to-NPL) for each individual detector agree well (i.e. to well within the combined random uncertainties) with the mean ratio, indicating that the consistency between the individual detectors was good.

Table 5 shows that at 632.8 nm the uncertainty associated with the DoE for UME is larger than the DoE itself i.e. the UME results at 632.8 nm are in good agreement with the reference value from the CCPR S3 Comparison. At 514.5 nm, however, the uncertainty associated with the DoE for UME is significantly smaller than the DoE, indicating that the results from UME provided during this comparison do not agree with the CCPR S3 reference value at this wavelength. This suggests that an unidentified systematic error was present in the UME measurements at this wavelength, or was introduced during the analysis of the results against the UME radiometer (e.g. by selection of incorrect values for the radiometer parameters). Following publication of Draft A, UME reassessed their data and believe that in their calculation software they may have mistakenly used the transmittance value for the vacuum window obtained at 633 nm for measurements made at 514 nm. This would fully account for the observed differences.

9. REFERENCES

[1] R. Goebel, M. Stock and R. Köhler, Report on the international comparison of cryogenic radiometers by means of transfer detectors. Rapport BIPM-2000/9, September 2000 - available on the BIPM website www.bipm.org.

[2] Protocol for bilateral comparison of cryogenic radiometers through calibration of trap detectors, CCPR WG-KC/04-10, April 2004.

APPENDIX A. REPORT FROM PILOT LABORATORY (NPL)

A.1 EXPERIMENTAL CONDITIONS AT NPL

- Cryogenic radiometer type: mechanically cooled, NPL design.
- Source: Kr Ion and HeNe gas laser
- Nominal power: 600 µW
- Beam diameter ($1/e^2$): 4.0 mm
- Temperature: 20 °C ± 0.5 °C

A.2 NPL UNCERTAINTY BUDGET

Table A.1 NPL uncertainty budget for optical power measurement using cryogenic radiometer.

Source of uncertainty	**Wavelength / nm**					
	356.4	**413.1**	**476.2**	**568.2**	**647.1**	**799.3**
	10^4 × relative standard uncertainty					
Cavity absorption	0.06	0.06	0.06	0.06	0.06	0.06
Brewster window transmittance	0.5	0.5	0.5	0.5	0.5	0.5
Brewster window scatter	0.05	0.05	0.05	0.05	0.05	0.05
Sensitivity of radiometer	0.06	0.06	0.06	0.06	0.06	0.06
Electric power measurement	0.1	0.1	0.1	0.1	0.1	0.1
Changes in scattered and thermal radiation	0.06	0.06	0.06	0.06	0.06	0.06
Measurement repeatability	0.51	0.24	0.18	0.16	0.29	0.27
Combined standard uncertainty	**0.7**	**0.56**	**0.56**	**0.54**	**0.56**	**0.6**

Table A.2 NPL uncertainty budget for the calibration of transfer trap detectors

Source of uncertainty	**Wavelength / nm**					
	356.4	**413.1**	**476.2**	**568.2**	**647.1**	**799.3**
	10^4 × relative standard uncertainty					
Optical power measurement by cryogenic radiometer	0.7	0.56	0.56	0.54	0.56	0.6
Detector DVM calibration	0.03	0.03	0.03	0.03	0.03	0.03
Detector DVM drift	0.03	0.03	0.03	0.03	0.03	0.03
Amplifier calibration	0.6	0.6	0.6	0.6	0.6	0.6
Amplifier drift	0.06	0.06	0.06	0.06	0.06	0.06
Beam size	0.3	0.3	0.3	0.3	0.3	0.3
Positional reproducibility	0.25	0.25	0.25	0.25	0.25	0.25
Measurement repeatability	0.11	0.25	0.19	0.16	0.26	0.23
Combined standard uncertainty (u_{NPL})	**1.05**	**0.97**	**0.96**	**0.94**	**0.95**	**0.98**

APPENDIX B. REPORT FROM PARTICIPANT LABORATORY (UME)

B.1 EXPERIMENTAL CONDITIONS AT UME

- Cryogenic radiometer type: Radiox, from Oxford Instrument Ltd.
- Sources: He-Ne laser and Ar-Ion laser
- Nominal power: 100 μW to 150 μW
- Beam diameter: approximately 2 mm
- Temperature: 23 ± 1.0 ^{0}C
- Relative Humidity: % (45.0 ± 10.0)

The traceability chain is based on absolute measurement of optical power using an Oxford Instruments/RADIOX electrical-substitution cryogenic radiometer system (ESCR) working at liquid helium temperature (4.2 K).

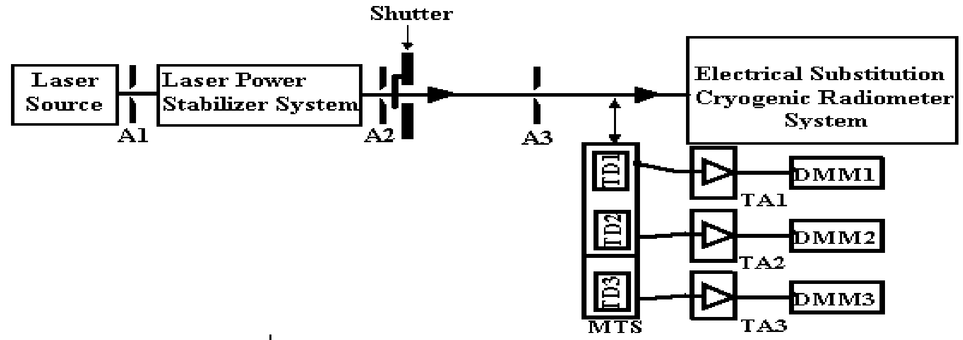
The radiometer was evacuated to a pressure of about 10^{-5} Pa (10^{-7} Torr) using a turbo molecular pumping system. The nitrogen and helium reservoirs were filled with liquid nitrogen and after 12 hours the helium reservoir was emptied and liquid helium was transferred into it. The cavity took about 6 hours to cool from 77 K (liquid nitrogen temperature) to 4.2 K (liquid helium temperature). The radiometer was maintained in the cooled condition and ready for immediate use.

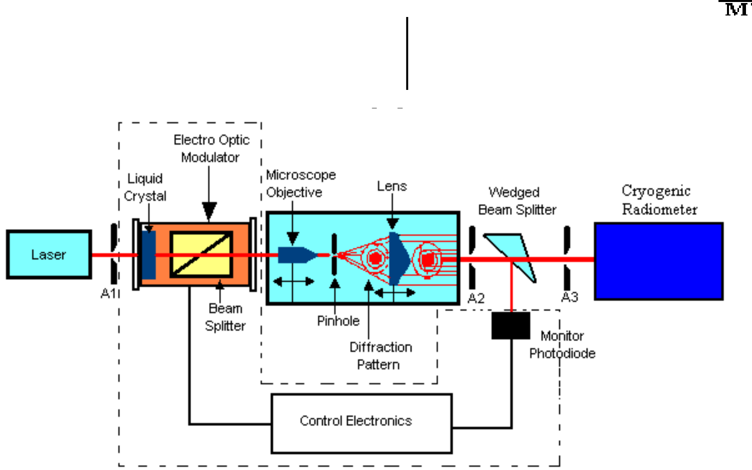
The accuracy of measurements using the cryogenic radiometer strongly depends on the power stabilization of the laser beam, cleaning and the transmittance measurements of radiometer entrance window and minimization of scattered light.

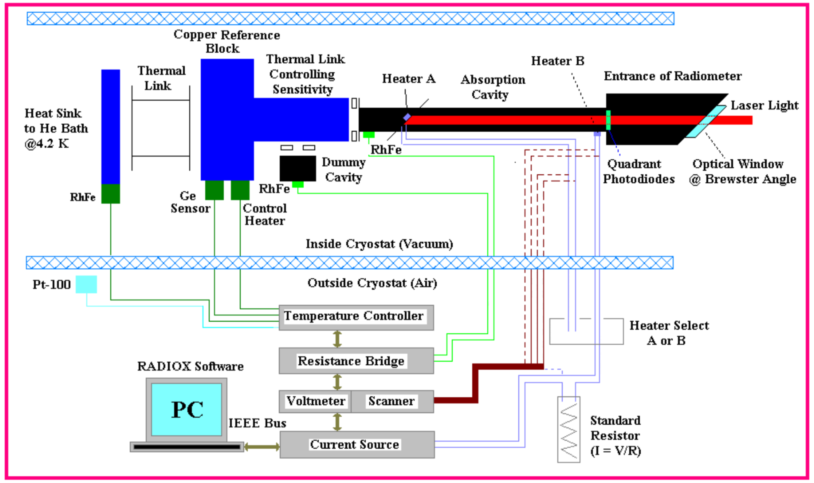
In order to compensate for fluctuations in the optical power and generate a geometrically well-defined Gaussian laser beam, a laser power stabilizer system (LPS) was used as shown in Figure B.1. A microscope objective, a pinhole (25 μm in diameter) and a collimating lens were used to produce a clean Gaussian laser beam with a desired dimension, approximately 2 mm in diameter.

The radiometer entrance window was released and cleaned using suitable solutions (e.g. ethanol) and lens paper using the drop and drag method and this process was repeated until the desired transmittance cleanliness was achieved. Then, the window was placed on a gimbal holder and adjusted to the Brewster angle. The absolute transmittance of radiometer entrance window was obtained by taking the ratio of the signals measured from a Si-based trap detector with and without the window in the path of the optical beam.

The stabilized and vertically polarized optical beam enters the radiometer through the window inclined to the Brewster angle. The part of the beam that is not aligned is therefore scattered due to the window and falls on the quadrant photodiodes. Precise adjustments were made until the beam properly entered the cavity and the signals from the quadrant photodiode were minimized. The optical power detected from these photodiodes was added and this result was noted as the correction value of scattered laser light for optical power measurements.







Cryogenic Radiometer System

Figure B.1 Responsivity measurement system. A1,A2 and A3 are precise apertures;TD1,TD2 and TD3 are measured trap detectors;TA1,TA2 and TA3 are transimpedance amplifiers;DMM1,DMM2 and DMM3 are digital multimeters; MTS is the motorized translation stage.

Optical power measurements were performed using a static substitution method. This method is based on sandwiching optical temperature between two electrical temperature points. In the static substitution method a measurement cycle consists of three optical points (which should all be at identical temperatures) and two electrical points calculated to be slightly above and slightly below the optical value. The procedure used to find the optical power for a measurement cycle by static substitution method is as follows:

a. The optical beam is applied to the cavity until its temperature stabilized.

b. The optical beam is turned off and an electrical current is applied so as to obtain the electrical temperature to be above the optical temperature.

c. The electrical current is turned off and the optical beam is applied again.

d. After temperature stabilization, a second electrical-substitution current is applied to obtain the electrical temperature below the optical temperature.

This cycle continues with optical-electrical signal (high) - optical-electrical signal (low). The optical power was then calculated by using equation (B.1) according to each group of optical power and its adjacent electrical powers.

$$P_{\mathrm{opt}} = P_{i\mathrm{E1}} + (P_{i\mathrm{E2}} - P_{i\mathrm{E1}})\frac{(T_{i,\mathrm{opt}} - T_{i\mathrm{E1}})}{(T_{i\mathrm{E2}} - T_{i\mathrm{E1}})} \qquad \text{(B.1)}$$

where P and T designate power and temperature respectively, the subscript opt represents optical measurement, iE1 and iE2 stand for first and second electrical measurements respectively in the i^{th} measurement cycle.

Since the optical radiation can be reduced by scattering $S(\lambda)$, the window transmittance $\tau(\lambda)$ the imperfect cavity absorbance $\alpha(\lambda)$ and the nonequivalence N, the measured optical power was corrected for these parameters using the following equation

$$P_{\mathrm{corr.opt}}(\lambda) = \frac{1}{\tau(\lambda)}\left[\frac{NP_{\mathrm{opt}}}{\alpha(\lambda)} + \mathrm{S}(\lambda)\right] \qquad \text{(B.2)}$$

In order to minimize errors from power fluctuations, measurement cycles were repeated. During the power measurement after four measurement cycles trap detectors were placed on the motorized translational stage and precisely moved into the laser path and their response in terms of voltage against the absolute power measured separately. Here responsivities of trap detectors were measured six times.

B.2. UME MEASUREMENT RESULTS

Type of Standard: Trap Detector **Detector Number:** NPL 11033T

Wave-length / nm	Round 1				Round 2			
	Respon-sivity / A W^{-1}	No. of measure-ments	Temp / °C	Uncer-tainty × 10^4	Respon-sivity / A W^{-1}	No. of measure-ments	Temp / °C	Uncer-tainty × 10^4
514.5	0.4133	6	24 ± 0.5	4.53	0.4131	10	23 ± 1.0	5.0
632.8	0.5086	6	24 ± 0.5	3.27	0.5086	10	23 ± 1.0	4.6

Type of Standard: Trap Detector **Detector Number:** NPL 11034T

Wave-length / nm	Round 1				Round 2			
	Respon-sivity / A W^{-1}	No. of measure-ments	Temp / °C	Uncer-tainty × 10^4	Respon-sivity / A W^{-1}	No. of measure-ments	Temp / °C	Uncer-tainty × 10^4
514.5	0.4133	6	24 ± 0.5	4.67	0.4131	10	23 ± 1.0	5.1
632.8	0.5085	6	24 ± 0.5	4.51	0.5086	10	23 ± 1.0	4.7

Type of Standard: Trap Detector **Detector Number:** NPL 11035T

Wave-length / nm	Round 1				Round 2			
	Respon-sivity / A W^{-1}	No. of measure-ments	Temp / °C	Uncer-tainty × 10^4	Respon-sivity / A W^{-1}	No. of measure-ments	Temp / °C	Uncer-tainty × 10^4
514.5	0.4133	6	24 ± 0.5	4.41	0.4131	10	23 ± 1,0	5.1
632.8	0.5086	6	24 ± 0.5	3.64	0.5085	10	23 ± 1,0	4.7

B.3. UME CORRECTION FACTORS

No additional correction factors were applied to the results other than as part of the calibration process as described in B.1.

B.4. UME UNCERTAINTY BUDGETS

UME provided separate uncertainty budgets for the first and second round of measurements, with those for the second round being higher than those for the first. The second round uncertainty budgets are given below and were used for the analysis of the results of this bilateral comparison (at each wavelength, the uncertainty for the detector with the highest uncertainty was used).

1- For NPL 11033T at 514.5 nm

Source of uncertainty	**$10^4 \times$ standard uncertainty**
Optical Temperature	0.32
Electrical Temperature	0.32
Electrical Power	0.30
Window Transmittance	0.95
Scattered Optical Power	0.93
Cavity Absorbance	0.05
Repeatability of optical power measurements	0.96
Non Equivalence	0.65
Multimeter	0.40
Transimpedance Amplifier Gain	0.40
Repeatability of responsivity measurements	1.62
Expanded uncertainty (*k*=2)	**5.04**

2- For NPL 11034T at 514.5 nm

Source of uncertainty	**$10^4 \times$ standard uncertainty**
Optical Temperature	0.32
Electrical Temperature	0.32
Electrical Power	0.30
Window Transmittance	0.95
Scattered Optical Power	0.93
Cavity Absorbance	0.05
Repeatability of optical power measurements	0.96
Non Equivalence	0.65
Multimeter	0.40
Transimpedance Amplifier Gain	0.40
Repeatability of responsivity measurements	1.68
Expanded uncertainty (*k*=2)	**5.12**

3- For NPL 11035T at 514.5 nm

Source of uncertainty	**$10^4 \times$ standard uncertainty**
Optical Temperature	0.32
Electrical Temperature	0.32
Electrical Power	0.30
Window Transmittance	0.95
Scattered Optical Power	0.93
Cavity Absorbance	0.05
Repeatability of optical power measurements	0.96
Non Equivalence	0.65
Multimeter	0.40
Transimpedance Amplifier Gain	0.40
Repeatability of responsivity measurements	1.69
Expanded uncertainty (*k*=2)	**5.13**

4- For NPL 11033T at 632.8 nm

Source of uncertainty	**$10^4 \times$ standard uncertainty**
Optical Temperature	0.41
Electrical Temperature	0.41
Electrical Power	0.38
Window Transmittance	0.92
Scattered Optical Power	0.88
Cavity Absorbance	0.05
Repeatability of optical power measurements	0.98
Non Equivalence	0.83
Multimeter	0.40
Transimpedance Amplifier Gain	0.40
Repeatability of responsivity measurements	1.12
Expanded uncertainty (*k*=2)	**4.62**

5- For NPL 11034T at 632.8 nm

Source of uncertainty	**$10^4 \times$ standard uncertainty**
Optical Temperature	0.41
Electrical Temperature	0.41
Electrical Power	0.38
Window Transmittance	0.92
Scattered Optical Power	0.88
Cavity Absorbance	0.05
Repeatability of optical power measurements	0.98
Non Equivalence	0.83
Multimeter	0.40
Transimpedance Amplifier Gain	0.40
Repeatability of responsivity measurements	1.18
Expanded uncertainty (*k*=2)	**4.68**

6- For NPL 11035T at 632.8 nm

Source of uncertainty	**$10^4 \times$ standard uncertainty**
Optical Temperature	0.41
Electrical Temperature	0.41
Electrical Power	0.38
Window Transmittance	0.92
Scattered Optical Power	0.88
Cavity Absorbance	0.05
Repeatability of optical power measurements	0.98
Non Equivalence	0.83
Multimeter	0.40
Transimpedance Amplifier Gain	0.40
Repeatability of responsivity measurements	1.15
Expanded uncertainty (*k*=2)	**4.65**