Bilateral Comparison of Luminous Intensity and Luminous Responsivity Between CSIRO (Australia) and SPRING (Singapore)

(KCDB reference No. CCPR-K3.a.1 and CCPR-K3.b.1)

Final Report

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Frank Wilkinson, Gan Xu, Yuanjie Liu and Hwee Lang Tan

Contents

1. Introduction

The Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia) and the Standards, Productivity and Innovation Board (SPRING Singapore) agreed in August 2003 to conduct a bilateral comparison on luminous intensity using a number of tungsten lamps as transfer standards and on luminous responsivity using a photometer as the transfer standard.

The aim of this bilateral comparison is to assess the equivalence of the luminous intensity scales between the two laboratories.

A technical protocol was produced that followed the guidelines established by the BIPM and takes account of the technical protocols of various key comparisons of luminous intensity and luminous responsivity organised by CIPM, APMP, etc.

The comparison and its protocol were approved by CCPR and registered with KCDB with a comparison no. CCPR-K3.a.1 for luminous intensity and no. CCPR-k3.b.1 for luminous responsivity.

2. Organisation

2.1 Participants

Address	Person in charge	Contact
CSIRO - National Measurement Laboratory † PO Box 218, Lindfield, Australia	Dr. Mark Ballico (Frank Wilkinson)	Tel: +61-612-9413 7300 Fax: +61-612-9413 7202 E-mail: Frank.Wilkinson@csiro.au
National Metrology Centre SPRING Singapore #1 Science Park Drive Singapore 118221	Dr Xu Gan (Liu Yuanjie)	Tel: +65-67739789 Fax: +65-67739804 E-mail: xugan@spring.gov.sg

Note: The CSIRO National Measurement Laboratory has recently been combined with the Australian Government Analytical Laboratories and the National Standards Commission to form the National Measurement Institute of Australia within the Department of Industry, Tourism and Resources.

CSIRO was the pilot laboratory.

2.2 Form of comparison

The comparison was principally carried out through the calibration of a group of three travelling standard lamps and a standard photometer (both lamps and detector prepared by CSIRO, they will be referred to as the artefacts in the following sections). A detail description of the artefacts is given in section 3 of this report.

The artefacts were initially calibrated by CSIRO. They were then hand-carried to SPRING Singapore for calibration. After the calibration at SPRING Singapore these artefacts were hand-carried back to CSIRO for a repeat calibration to monitor the drift.

There was no reported damage to the lamps, photometer or their packaging when being hand carried between the CSIRO and SPRING laboratories. All three lamps and the photometer appeared to operate normally at both laboratories.

All of the measurements were done over the period 11 November 2003 – 17 December 2003.

3. Description of the artefacts

There are two types of artefacts. The first type is tungsten halogen lamps and the second type is a LMT photometer without diffuser.

The tungsten halogen lamps are automotive type H1 rated at 12V 100W and run at about 10V 8A with a nominal operating correlated colour temperature of 2856K.

Each lamp was operated in constant current mode at a direct current for which its correlated colour temperature is closest to 2856K.

Each lamp was mounted on a 3-pin kinematic base which stood on a round brass base of diameter 120 mm and height 25 mm. For the luminous intensity measurements, a horizontal optical axis was defined that is 270 mm above the bottom surface of the brass base. The lamp height was adjusted so that the optic axis passed through the centre of the lamp filament. The lamp orientation was adjusted so that the optic axis was normal to the plane of the front surface of the heat-sink supporting the lamp (the plane of the rear surface, which is parallel to the front surface, could also be used). The lamps were tested using a distance measured from the mean plane of the filament. For convenience, the offset distance between the mean filament plane and the front surface of the heat-sink was supplied with each lamp. A photograph of one of the lamps mounted on the base is shown in Figure 3.1

Two electrical leads soldered to the lamp pins connect them to two large terminals in the base for current and voltage connections.

The photometer is LMT type P15FOT with fine correction to $V(\lambda)$ response. It has a circular body of 50 mm diameter with a nominal aperture diameter of 15 mm. The reference plane of the photometer is 3.07 mm, measured as a distance back from the front surface of the housing. It may be mounted on a plate with a ¼" – 20 screw.

The photometer comes with an adaptor for temperature stabilisation that requires 24-30 DCV (maximum current 300 mA) power supply. It has a f_1' value of 2 % for CIE Illuminant A. A LEMO connector adapted to BNC for signal connection was provided.

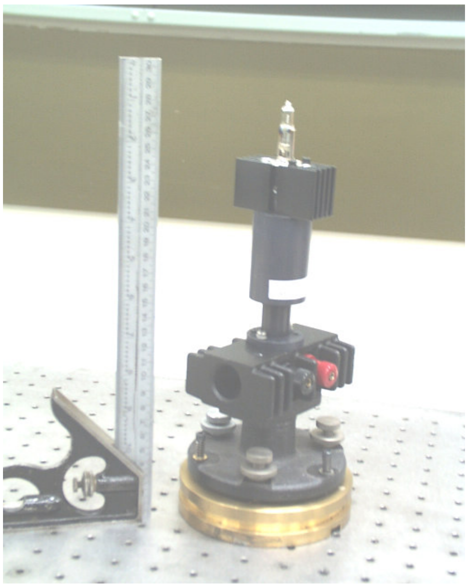


Figure 3.1 Transfer standard lamp with lamp support

4. Measurement conditions

4.1 Laboratory environment

Measurements at CSIRO were reported to be done at an ambient temperature of 21º ± 0.5ºC and relative humidity of 50 ± 10%. At SPRING the reported temperature was 23º ± 2ºC and relative humidity was 60 ± 10%. These conditions are considered to be suitable for these comparisons and the differences are not significant. The exact temperatures of the laboratories during the time of the measurements are given together with the results in Appendices A2.1 and A2.2.

4.2 Measurands

The two measurands involved in this bilateral comparison are the luminous intensity of lamps and the luminous responsivity of photometers to the CIE Illuminant A.

The first measurand is the luminous intensity, in candela, of a tungsten halogen lamp at a specified given direction and running at CIE Illuminant A. The distance of measurement was 2.5 m, measured between the filament plane of the lamp and the reference plane of the detector. For each lamp the luminous intensity was measured for a defined operating current of approximately 8 A passing through the filament of a tungsten halogen lamp rated at 100W.

The second measurand is the luminous responsivity, with the unit of nA / lx, of a photometer (a $V(\lambda)$ corrected detector). The response of the photometer was made at a field of illuminance of approximately 50 lx, with a colour temperature of 2856K (CIE Illuminant A).

4.3 Alignment of the artefacts and measurement instructions

Details of these are given in the protocol.

5. Analysis of measurement results

Details of the measurement results are given in Appendix 2.

5.1 SPRING Summary

Table 5.1 SPRING results for luminous intensity lamps

ID	Luminous intensity (cd, average of 3 runs)	% std of mean of 3 measurements	Standard Uncertainty (%, k=1)
ETH1	71.22	0.11	0.32
ETH2	61.31	0.08	0.32
ETH3	77.25	0.04	0.32

Table 5.2 SPRING results for photometer

ID	Luminous responsivity (nA/lx, average of 3 runs)	% std of mean of 3 measurements	Standard Uncertainty (%, k=1)
LMT	38.65	0.06	0.29

5.2 CSIRO Summary

Table 5.3 CSIRO results for luminous intensity lamps

ID	Luminous intensity (cd, average of 3 runs)	% std of mean of 3 measurements	Standard Uncertainty (%, k=1)
ETH1			
Round 1	71.198	0.031	0.21
Round 2	71.133	0.016	0.21
Difference (%)	0.091		
mean	71.165		0.21
ETH2			
Round 1	61.157	0.076	0.21
Round 2	61.190	0.035	0.21
Difference (%)	0.053		
mean	61.173		0.21
ETH3			
Round 1	77.274	0.011	0.21
Round 2	77.198	0.016	0.21
Difference (%)	0.098		
mean	77.236		0.21

Table 5.4 CSIRO results for photometer LMT 039638

Measurement round	Luminous responsivity (nA/lx, average of 3 runs)	% std of mean for 6 measurements from 2 rounds	Standard Uncertainty (%, k=1)
1	38.622	0.008	0.20
2	38.618		0.20
Difference (%)	0.011		
mean	38.620		0.20

5.3 Comparison of results

Table 5.5 Comparison of values of luminous intensity and luminous responsivity measured by SPRING and CSIRO

Lamp	SPRING mean	CSIRO mean	Ratio SPRING / CSIRO	Combined standard uncertainty (%)
	Luminous intensity (cd)			
ETH1	71.22	71.165	1.00074	0.38
ETH2	61.31	61.173	1.00216	0.38
ETH3	77.25	77.236	1.00015	0.38
		Mean ratio	1.00102	
Photometer	Luminous responsivity (nA/lx)			
LMT039638	38.65	38.62	1.00079	0.35

In the following figures the lamp intensities and photometer responsivities that were measured by each laboratory are shown with points connected by heavy lines. In the figures for the lamps, the finer lines (series 4-6) are changes in intensity from the initial measurement that have been calculated based on changes in the lamp voltage. This has been done to see if the measured changes in intensity are well correlated with changes in the lamp electrical power.

The error bar shown with the CSIRO round 1 data is the estimated range of the standard uncertainties for random or type A sources of error. The error bar shown with the SPRING data is the range of the standard uncertainty in each of the measurements. The final error bar represents the range of the combined standard uncertainties of both of the laboratories. These will be discussed in the following section.

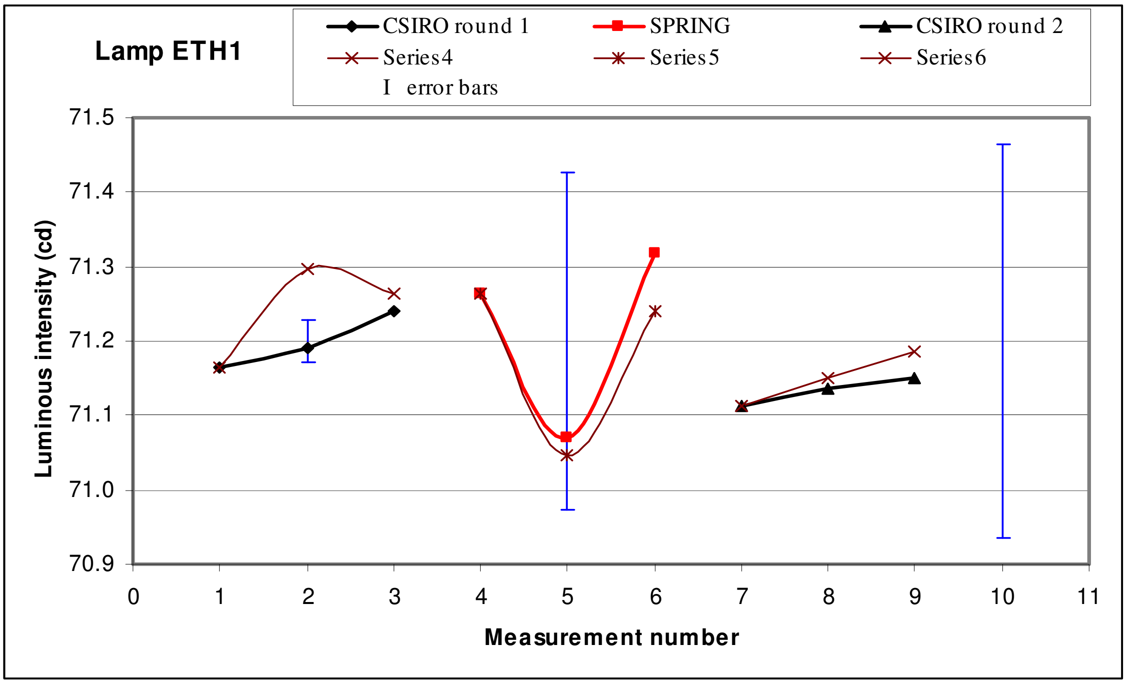


Figure 5.1 Comparison of measurement results for the lamp ETH1. Finer lines show predicted changes in intensity based on lamp voltage changes. Error bars represent CSIRO random uncertainties, SPRING total uncertainties and combined total uncertainties.

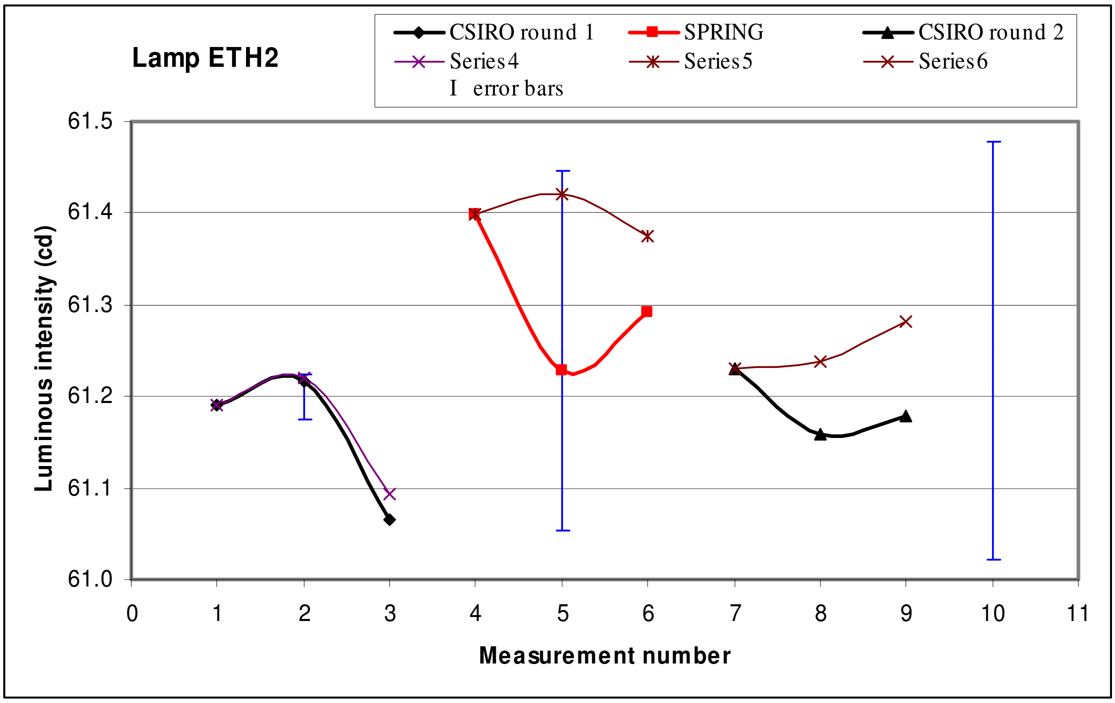


Figure 5.2 Comparison of measurement results for the lamp ETH2. Finer lines show predicted changes in intensity based on lamp voltage changes. Error bars represent CSIRO random uncertainties, SPRING total uncertainties and combined total uncertainties.

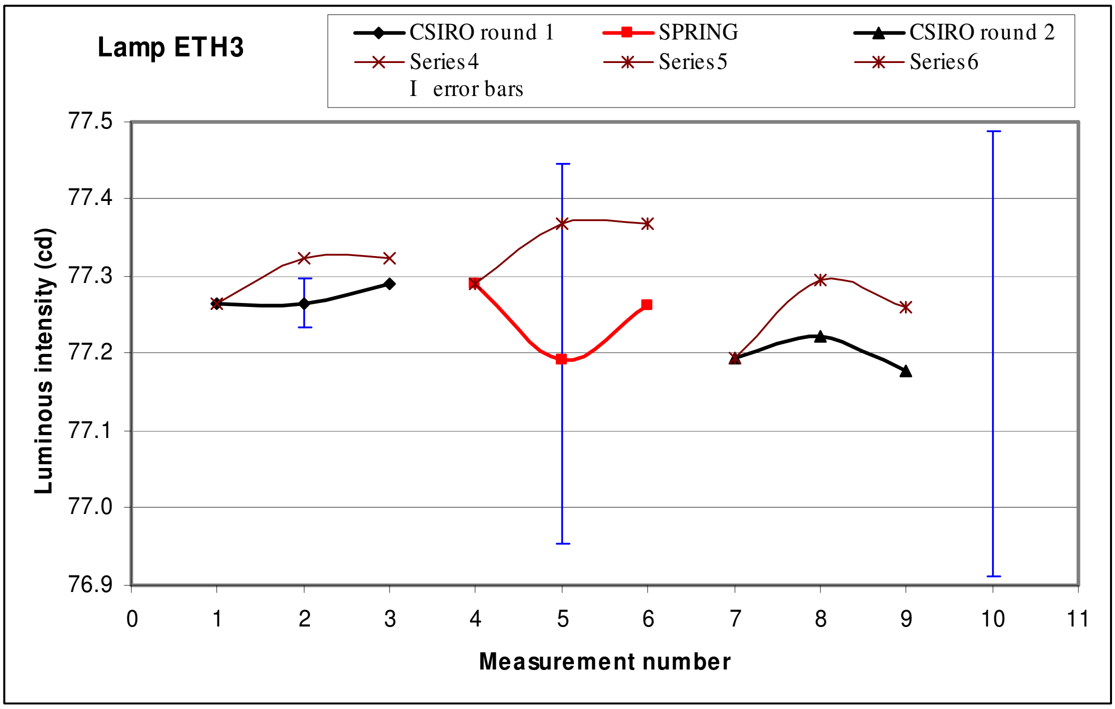


Figure 5.3 Comparison of measurement results for the lamp ETH3. Finer lines show predicted changes in intensity based on lamp voltage changes. Error bars represent CSIRO random uncertainties, SPRING total uncertainties and combined total uncertainties.

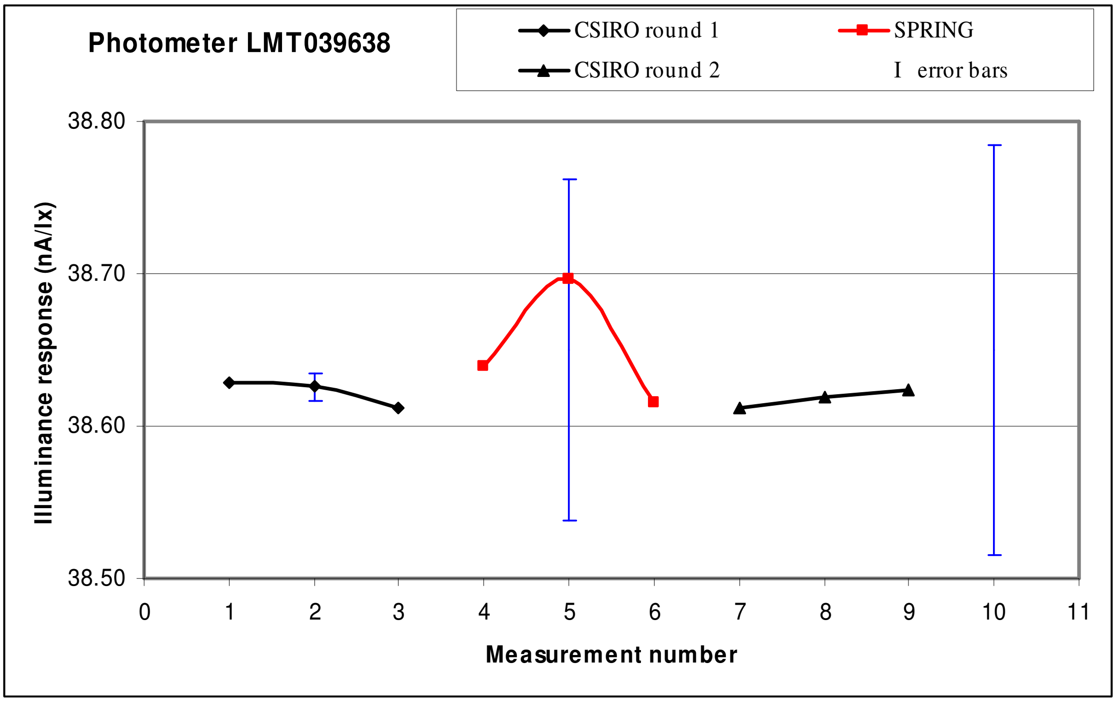


Figure 5.4 Comparison of measurement results for the photometer LMT039638. Error bars represent CSIRO random uncertainties, SPRING total uncertainties and combined total uncertainties.

6. Measurement uncertainties

The uncertainties of measurement have been estimated according to the ISO Guide to the Expression of Uncertainty in Measurement. Some details of considerations to be taken that apply to these particular measurements are given in Appendix A.1.

6.1 CSIRO uncertainties

Each measurement involved the use of a photometer that was calibrated for luminous responsivity using four laboratory reference standards of luminous intensity. The same four lamps were repeatedly used before each measurement. The measurement uncertainties are therefore correlated by the uncertainty in the laboratory scale maintained by this combination of four lamps.

Table 6.1 Uncertainty of measurement for luminous responsivity of photometer LMT039638

Parameter	Type A Uncertainty in Value %	Type B Uncertainty in Value %	Uncertainty in Units of measurement %
Repeatability of Ref.	0.022		0.022
Transfers to artefact	0.007		0.007
Agreement between reference lamps (ESDM for 4 lamps)		0.057	0.057
Base unit		0.17	0.170
Base unit drift in 7 years		0.035	0.035
Positioning of artefact		0.002	0.002
Precision of picoammeter for photocurrent measurement		0.005	0.005
Reference Illuminance uncertainty due to source current uncertainty		0.063	0.063
RMS total	0.024	0.193	0.195

Table 6.2 Uncertainty of measurement for luminous intensity of lamps

Parameter	Type A Uncertainty in Value %	Type B Uncertainty in Value %	Uncertainty in Units of measurement %
Reference photometer (see Table 6.1)		0.195	0.195
Positioning of artefact (including distance and angular orientation)		0.050	0.050
Laboratory temperature	0.04		
Transfer measurement	0.010		0.010
Photometer Linearity		0.010	0.010
RMS total	0.041	0.202	0.206

6.2 **SPRING uncertainties**

All individual components of the trap photometers were fully characterised and their contributions to the uncertainty budget were carefully analysed. The final uncertainty budget is given below:

Table 6.3 Uncertainty Calculation for Trap Photometer Luminous Responsivity:

$u(x_I)$	Source of uncertainty	Value of $u(x_i)$ %	c_i	Probability distribution	k	$u_i(y)$ %	DoF
u(1)	Absolute Spectral Responsivity at 555nm (B)	0.22	1	normal	2	0.11	∝
u(2)	Absolute Spectral Transmittance at 555nm (B)	0.42	1	normal	2	0.21	∝
u(3)	Aperture Area Measurement (B)	0.16	1	normal	2	0.08	∝
u(4)	Correction Factor (B)	0.15	1	normal	2	0.075	∝
$u_c(y)$	combined uncertainty, %			normal		0.26	
U(y)	expanded uncertainty, %			normal	2	0.52	

Table 6.4 Uncertainty Calculation for Luminous Intensity Standard Lamps:

$u(x_I)$	Source of uncertainty	Value of $u(x_i)$ %	c_i	Probability distribution	k	$u_i(y)$ %	DoF
u(1)	Uncertainty of trap photometers (B)	0.52	1	normal	2	0.26	∝
u(2)	Agreement btw standards (A)	0.08	1	normal	1	0.08	5
u(3)	Uncertainty of distance measurement at 2.5m (B)	0.02	2	rectangular	1.73	0.02	∝
u(4)	Accuracy of electrometer(B)	0.1	1	rectangular	1.73	0.058	∝
u(5)	Measurement unc of electrical current of the lamps(B)	0.02	6.25	rectangular	1.73	0.07	∝
u(6)	Repeatability of measurement (A)	0.03	1	normal	1	0.03	39
$u_c(y)$	combined uncertainty, %			normal		0.289	
U(y)	expanded uncertainty, %			normal	2	0.58	

Table 6.5 Uncertainty of measurement for luminous intensity of lamps

Parameter	Type A Uncertainty in Value %	Type B Uncertainty in Value %	Uncertainty in Units of measurement %
Repeatability of Ref.	0.02		0.02
Repeatability of artefact	0.15		0.15
Base unit		0.26	0.26
Positioning of artefact		0.023	0.023
Transfer measurement		0.096	0.096
Accuracy of electrometer for photocurrent output		0.058	0.058
RMS total	0.15	0.28	0.32

Table 6.6 Uncertainty of measurement for luminous responsivity of LMT photometer

Parameter	Type A Uncertainty in Value %	Type B Uncertainty in Value %	Uncertainty in Units of measurement %
Repeatability of Ref.	0.02		0.02
Repeatability of artefact	0.002		0.002
Base unit		0.26	0.26
Positioning of artefact		0.023	0.023
Transfer measurement		0.096	0.096
Accuracy of electrometer for photocurrent output		0.058	0.058
RMS total	0.02	0.29	0.29

7. Summaries of measurement traceability and procedures

7.1 CSIRO measurement scales

Luminous intensity units were last realised at CSIRO in 1997 with a relative standard uncertainty value of 0.17% (1). The units are based on a responsivity transfer between the CSIRO primary reference cryogenic radiometer and a 4 element silicon transmission trap at 9 laser wavelengths between 476.2 nm and 676.4 nm. Trap responsivities over the visible wavelength range between 360 nm and 830 nm have been calculated by extrapolation of the fit to the responsivity data at the selected wavelengths. The extrapolation was also checked with reference to relative spectral responsivity units held on bolometers.

Units of spectral radiant flux responsivity were converted to units of spectral irradiance responsivity using a precision aperture calibrated in the length standards project at CSIRO. Irradiance responsivity units were transferred to three thermostatic $V(\lambda)$ corrected photometers using a ratio technique with a filtered Hg line source. The relative spectral response of the photometers was also characterised traceable to bolometers and the transmission trap. The candela was realised by transfer from the photometers to a series of QH photometric standard lamps operating at approximately CIE Source A. The spectral distribution of the QH standards was determined with reference to a blackbody operating at a distribution temperature of approximately 2700 K. The candela is maintained on a network of 18 lamps and 7 photometers at specified distance.

Reference standards used for the comparison and optical and traceability diagrams are given in Appendix 3.1.

7.2 **SPRING measurement scales**

The new SPRING luminous intensity scale is essentially detector based and traceable to spectral responsivity scale based on a cryogenic radiometer, though the realisation also relies on the determination of the aperture area and spectral irradiance measurement for calculation of the spectral mismatch factor. Three trap photometers are used each of which consists of a three- element, reflection type trap detector made of silicon photodiodes (Hamamatsu 1337-1010 BQ) , a precision aperture with a nominal diameter 4mm and a temperature stabilised $V(\lambda)$ correction filter ($f_1' < 1.5\%$, UV and IR response u & $r < 0.2\%$, operating temperature 28 ± 0.1ºC).

The spectral responsivity of each trap detector from 380nm – 780 nm was measured using our spectral responsivity calibration facility based on a double-grating monochromator (5nm bandwidth and 5 nm interval) against two transfer silicon photodiodes which were calibrated using a cryogenic absolute radiometer.

The spectral transmittance of the filter at 28ºC from 380 nm to 780 nm was measured by a Perkin-Elmer Lambda 900 spectrometer with a 5 nm bandwidth (1 nm in 550 – 560nm for determination of the peak value).

The spectral responsivity of the photometer [$s(\lambda)=s_{\mathrm{rel}}(\lambda)\cdot s(555)$] was obtained by multiplying the spectral responsivity of the trap detector by the spectral transmittance of the $V(\lambda)$ correction filter.

The luminous responsivity of each trap photometer, s_v, is determined by

$$s_v = \frac{A \cdot s(555)}{K_m \cdot F}$$

where
A – aperture area in the photometer;
$s(555)$ – absolute responsivity of the photometer at the peak wavelength 555nm;
F - colour correction factor of the photometer:

$$F = \frac{\int V(\lambda)\cdot S_A(\lambda)\mathrm{d}\lambda}{\int s_{rel}(\lambda)\cdot S_A(\lambda)\mathrm{d}\lambda}$$

$S_A(\lambda)$ – relative spectral irradiance of the illuminating source – CIE illuminant A;
$s_{rel}(\lambda)$ – relative spectral responsivity of the photometer.

The luminous intensity of a tungsten incandescent lamp with a distribution temperature 2856 K can therefore be determined by

$$I_v = \frac{i\cdot d^2}{s_v}$$

where
i – photo-current from the trap photometer under the illumination of the lamp
d – distance between the lamp filament to the reference plain of the trap photometer
s_v – luminous responsivity of the trap photometer.

The luminous intensities of the lamps were calculated from measurements of their illuminances of different trap photometers for the three measurements. The luminous responsivity of the LMT photometer was measured by direct substitution with the three trap photometers when illuminated by a Wotan Wi41/G lamp at the distance of 2.5 m.

Reference standards used for the comparison and optical and traceability diagrams are given in Appendix 3.2.

8. Discussion

The measurements of the lamp intensities at CSIRO were done in both rounds by calibrating a photometer – the LMT039638 photometer used here, using a group of reference intensity standard lamps, and then using it to measure the three lamp intensities. This process was then repeated twice giving three sets of measurements. All of the measurements within each set are highly correlated. Intensities for a lamp or responsivities for the photometer between the six measurements have less correlation but the total uncorrelated uncertainties in the values are quite low as shown in Figs 5.1 to 5.4.

The distributions of lamp intensities measured by CSIRO and shown in Figs 5.1 to 5.3 do not have similar shapes as would be expected if changes were mainly due to correlated changes in the photometer calibration. Neither are the changes well correlated with the changes in measured lamp voltage. In only two of the total of nine measurements at both laboratories can it be said that the changes in intensity are well correlated with voltage changes.

The uncorrelated uncertainties calculated by CSIRO for these measurements, mainly for random effects, are insufficient to cover the ranges of the lamp intensities that have been measured. There is greater consistency in the CSIRO measurement of the photometer responsivities, with the range of the six values being covered by the uncorrelated uncertainties when estimated at a 95% confidence interval.

Each of the measurements at SPRING was done using a separate trap photometer. Transfer uncertainties for these measurements were quite small, so all measurements from a particular trap photometer are highly correlated. The order of use of the photometers for most of the lamp tests was TRAP-2, TRAP-1, TRAP-3 so this order has been used in the preparation of the above figures. Figures 5.1 to 5.3 show good correlation of the relative intensities of the lamps measured with these photometers. The result for the measurements of the LMT photometer responsivity also correlates well with the lamp results. Any increase in the unit of intensity or illuminance results in a decrease in the unit of detector responsivity.

The ranges of values measured at SPRING are well covered by the ranges of uncertainties in the measurements, which in this case are the sum of the uncertainties in the calibrations of the different components of the three photometers, the levels of correlation of which it is difficult to estimate here.

For two of the lamps and the photometer, the difference in the mean intensity or responsivity measured by SPRING and that measured by CSIRO was less than 0.1% of the value. For the third lamp it was 0.2%. For this lamp the total range in the intensities measured at CSIRO was also larger than for the other two lamps.

The spread of measured values from the two laboratories for two of the lamps overlaps well, and for the third lamp and the photometer the two ranges intersect. For each artefact the total range of measured values is well within the calculated combined standard uncertainty.

The ratios of measured units: SPRING/CSIRO for luminous intensity and luminous responsivity should be close to the inverse of one another if both laboratory scales are based on the same base units. Therefore, from the mean values given in Table 5.5, the inconsistency in the two results is at a level of 0.18%. Removing the correlated components from each scale in each laboratory, the combined type A random uncertainties for the two laboratories for the luminous intensity measurements is 0.155%, and for the luminous response measurements it is 0.03%. The combined random uncertainty when comparing these two results is then 0.16%. The difference of 0.18% barely exceeds this standard uncertainty.

9. Link with CCPR KCRV values

CSIRO took part in two CCPR key comparisons in 1997-98 relevant to these bilateral comparisons: the K3.a comparison of luminous intensity (2) and the K3.b comparison of luminous responsivity (3). An additional APMP comparison of luminous responsivity was held in 1999-2000 with CSIRO as the pilot laboratory (4). The results of the first two of these comparisons are shown in Fig 9.1.

SPRING took part in the APMP comparison, and the participants were linked with degrees of equivalence to the KCRV of the K3.b key comparison, but at that time SPRING was using a scale based on standards traceable to BIPM. The scale used for the current bilateral comparison is a new fully independent scale so the previous result is no longer relevant.

Table 9.1 Performance of CSIRO in CCPR key comparisons in 1997-1998

	Luminous intensity	Luminous responsivity
Ratio: CSIRO/KCRV	0.9993	1.0009
Standard uncertainty	0.30 %	0.19 %

The results for CSIRO in the two key comparisons are given in Table 9.1. They are actually highly consistent, since a low value of the luminous intensity unit relative to the KCRV would result in a high value in the luminous responsivity unit if both units were derived from the same base unit, the candela.

Since 1997, the CSIRO scale of illuminance has been maintained by four standard lamps, Philips type 6369R 30V 250W (5). In the new realisation of our scale in 1997, we showed that the value of our candela as maintained by these same four lamps had not changed by more than 0.05% since 1988 when it was also established by reference to an electrical substitution radiometer. Given the agreement between the lamps since 1997, the very small running time of these lamps and the drift rate that was established between 1988 and 1997, it is assumed that a group drift rate of not more than 0.005% / year has been maintained. Uncertainties for the disagreement within the group of four lamps and for this possible drift over the past 7 years have been included in the CSIRO budget for the luminous intensity unit in Table 6.1.

The ratios SPRING/CSIRO obtained in this bilateral comparison and given in Table 5.5 must be multiplied by 0.9993 for luminous intensity and by 1.0009 for luminous responsivity to obtain SPRING equivalence to the CCPR key reference values.

The SPRING degrees of equivalence to the CCPR KCRVs from the key comparisons in 1997-98 have been calculated from the ratios given in Tables 5.5 and 9.1 and are given in Table 9.2.

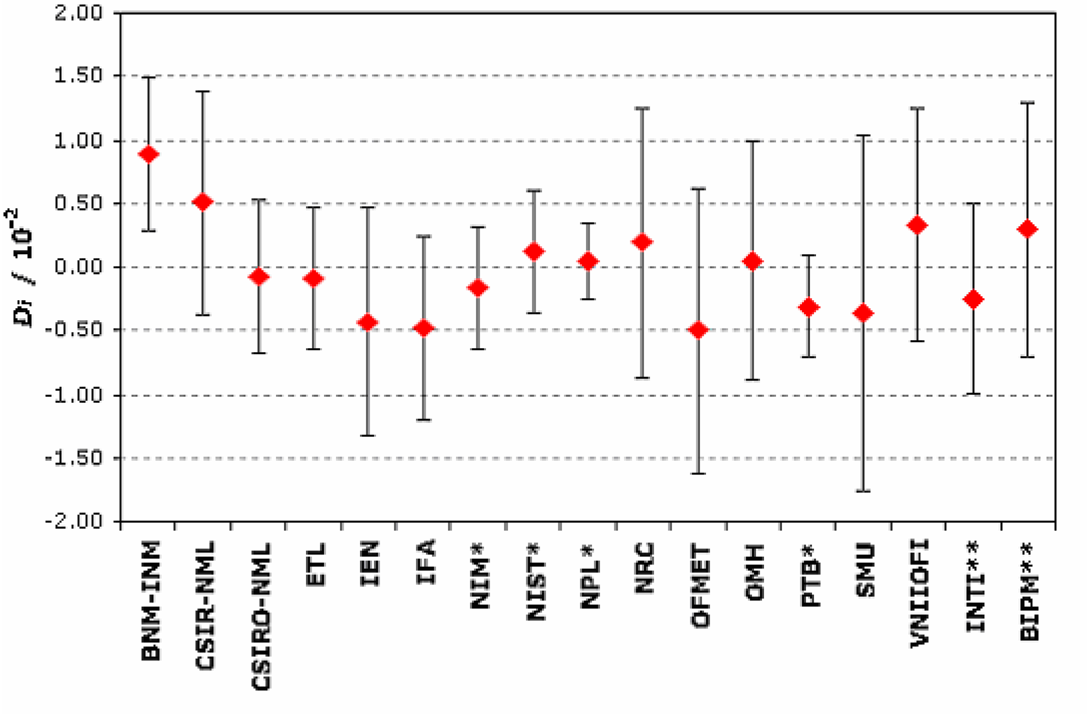
The CSIRO units that have been used in both the APMP comparison of 2000 and this current bilateral comparison are strongly correlated by the common uncertainty in the base unit. This has a standard uncertainty of 0.17%. The uncertainties in the SPRING degrees of equivalence to the KCRV values must be calculated from the quadratic sums of the SPRING uncertainties calculated for the bilateral comparison and the total of the uncorrelated components of the CSIRO uncertainties calculated for both the CCPR-K3.a key comparison and the current bilateral comparison. These uncertainties and the total standard uncertainties of the SPRING degrees of equivalence are also shown in Table 9.2.

Table 9.2 Degrees of equivalence and their standard uncertainties for SPRING units of luminous intensity and luminous responsivity relative to the KCRVs of the 1997-98 CCPR key comparisons K3.a and K3.b.

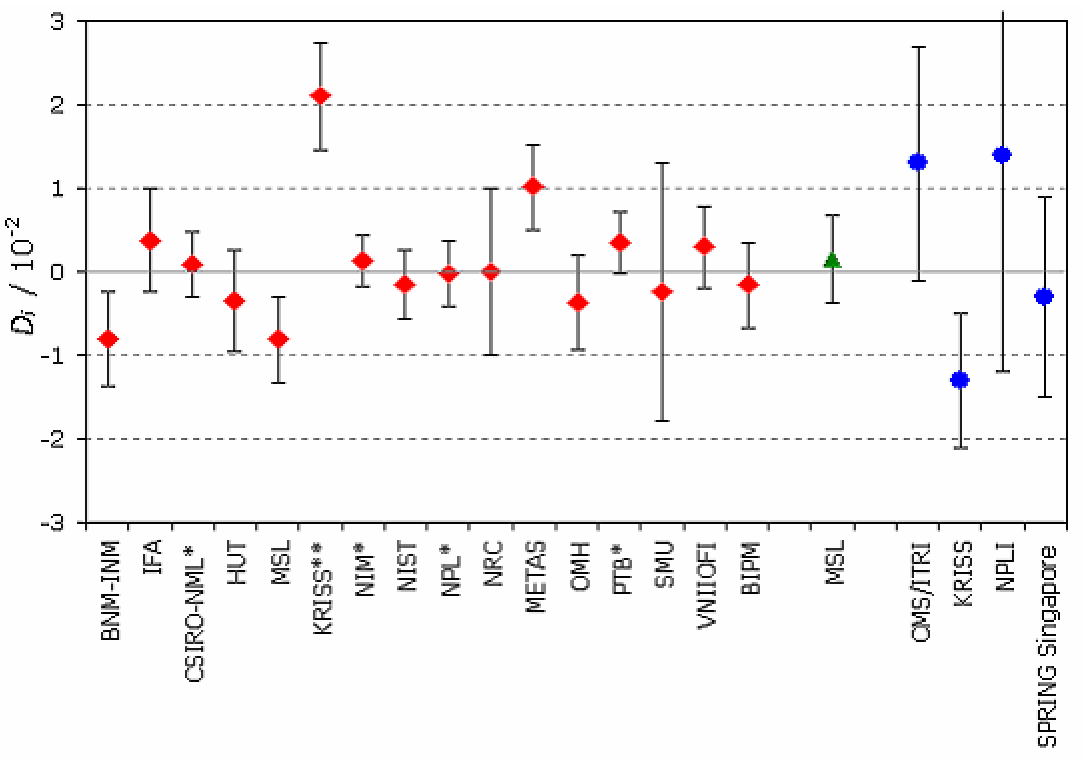
Measurand	Degrees of equivalence of SPRING units to CCPR KCRV values	Standard uncertainties (%)			
		CSIRO (uncorrelated) in		SPRING	SPRING
		K3.b key comparison	CSIRO-SPRING comparison	CSIRO-SPRING comparison	Total uncertainty in degrees of equivalence
Luminous intensity	1.0003	0.03	0.048	0.32	0.33
Luminous responsivity	1.0017	0.06	0.024	0.29	0.30

Degrees of equivalence D_i and expanded uncertainty U_i (k = 2)

MEASURAND : Luminous intensity CCPR-K3.a 1997-98



MEASURAND : Luminous responsivity CCPR-K3.b & APMP.PR-K3.b (1998 and 2000)



Blue circles: APMP.PR-K3.b participants only.

Figure 9.1 Results of CCPR K3.a and K3.b key comparisons and APMP.PR K3.b regional comparison showing participants degrees of equivalence to the key reference values.

10. Conclusions

The laboratory units of luminous intensity and luminous responsivity are in agreement well within their combined standard uncertainties. The difference in the unit of intensity, averaged over the use of three transfer lamps, is 0.10%. The difference in the unit of responsivity from the use of a single photometer is 0.08%. The combined standard uncertainties for these comparisons are, respectively, 0.37% and 0.35%.

The degrees of equivalence of the SPRING units relative to the KCRV values from the 1997-98 CCPR key comparisons are 1.0003 ± 0.0033 for the unit of luminous intensity and 1.0017 ± 0.0030 for luminous responsivity (k = 1).

The components of random uncertainty in the measurement of the lamp intensities at CSIRO appear to be underestimated. Any necessary increase in random uncertainty would not add significantly to the total uncertainty for the laboratory.

The results from the lamp ETH2 suggest that it is not quite as stable as the other two lamps, but the increased range of intensities measured for this lamp or the increased difference in its mean intensity between the two laboratories are considered to be insignificant compared with the magnitude of the total uncertainties.

CSIRO's experience with the six measurements of the photometer responsivity, where the total range was only 0.045%, suggests that a photometer such as this is much more reliable than the lamps as a transfer standard for this type of comparison.

11. References

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A. Appendices

A.1 Analysis of uncertainties

In order to achieve optimum comparability, a list containing the principal influence parameters for calibration of luminous intensity of tungsten lamps and the luminous responsivity of photometers are given below. All values have been given for a coverage factor of k=1.

Type A

Repeatability of reference standard – the standard deviation of a single set of measurements made on the reference standard without realignment.

Repeatability of transfer standard - the standard deviation of a single set of measurements made on the transfer standard without realignment.

Type B

Uncertainty of the base unit – This is the total uncertainty of the participant's underpinning scale as disseminated by them. This should include the uncertainty in the primary SI realisation, or in the case of scale originating from another laboratory, the uncertainty of the scale disseminated to it by that laboratory and this originating laboratory should be referenced. It is assumed that this will include all uncertainties associated with the measurement facility e.g. linearity, stray light, positioning of reference standards etc.

Uncertainty due to the positioning of the artefact – this is the uncertainty due to the positioning and alignment of the artefact.

Uncertainty of the transfer measurement – this is the uncertainty involved in the transfer measurement of the artefact. It should include those due to source current measurement, short term drifts of reference standards, etc.

Other relevant components – this can be any other uncertainty components a participant believes that they should be taken into account.

A.2 Detailed measurement results

Transfer standard deviations are for the individual measurement. Uncertainties are total standard uncertainties for the individual measurement. Cumulative hours are total burning time since **start of the comparison**.

A.2.1 Round 1 measurements at CSIRO

Table A.2.1 Results of individual measurements of lamp luminous intensities and photometer luminous responsivity during round 1 tests at the CSIRO laboratory

Reference number of artefact (lamp): ETH1 Ambient temperature: 21 ± 1 °C

Measurement Number	Luminous Intensity (cd)	Current (A)	Voltage (V)	Transfer Std Dev. %	Number of Readings	Uncertainty % (k=1)	Cumulative Burn Time (H)
1	71.164	5.935	8.814	0.0102	20	0.21	0.18
2	71.189	5.935	8.820	0.0091	20	0.21	0.45
3	71.239	5.935	8.818	0.0037	20	0.21	0.75
Mean	**71.198**	**5.935**	**8.817**	**0.031**	**(ESDM % of 3 measurements)**		

Reference number of artefact (lamp): ETH2 Ambient temperature: 21 ± 1 °C

Measurement Number	Luminous Intensity (cd)	Current (A)	Voltage (V)	Transfer Std Dev. %	Number of Readings	Uncertainty %	Cumulative Burn Time (H)
1	61.190	4.983	8.281	0.0055	20	0.21	0.18
2	61.216	4.983	8.283	0.0050	20	0.21	0.40
3	61.065	4.983	8.277	0.0039	20	0.21	0.68
Mean	**61.157**	**4.983**	**8.280**	**0.076**	**(ESDM % of 3 measurements)**		

Reference number of artefact (lamp): ETH3 Ambient temperature: 21 ± 1 °C

Measurement Number	Luminous Intensity (cd)	Current (A)	Voltage (V)	Transfer Std Dev. %	Number of Readings	Uncertainty %	Cumulative Burn Time (H)
1	77.265	5.931	8.825	0.0067	20	0.21	0.18
2	77.266	5.931	8.827	0.0078	20	0.21	0.45
3	77.291	5.931	8.827	0.0042	20	0.21	0.73
Mean	**77.274**	**5.931**	**8.826**	**0.011**	**(ESDM % of 3 measurements)**		

Reference number of artefact (photometer): LMT 039638 Ambient temperature: 21 ± 1 °C

Measurement Number	Luminous Responsivity nA / lx	Illuminance Level lx	Colour temp. of Source	Transfer Std Dev. %	Number of Readings	Uncertainty %
1	38.629	44.76	2856	0.0050	80	0.20
2	38.626	44.76	2856	0.0057	80	0.20
3	38.611	44.76	2856	0.0068	80	0.20
Mean	**38.622**	**44.76**	**2856**	**0.014**	**(ESDM % of 3 measurements)**	

A.2.2 Measurements at SPRING

Table A.2.2 Results of individual measurements of lamp luminous intensities and photometer luminous responsivity from tests done at the SPRING laboratory

Reference number of artefact (lamp): ETH1 Ambient temperature: 23 ± 2 ℃

Reference photometer	Test lamp Luminous Intensity (cd)	Lamp Current (A)	Lamp Voltage (V)	Transfer Std Dev. %	Number of Readings	Uncertainty (%) (*k*=1)	Cumulative Burn Hrs
Trap-2	71.264	5.935	8.826	0.051	40	0.32	3.00
Trap-1	71.071	5.935	8.817	0.027	40	0.32	3.83
Trap-3	71.318	5.935	8.825	0.014	40	0.32	4.58
mean	**71.218**			**0.11**	**(ESDM % of 3 measurements)**		

Reference number of artefact (lamp): ETH2 Ambient temperature: 23 ± 2 ℃

Reference photometer	Test lamp Luminous Intensity (cd)	Lamp Current (A)	Lamp Voltage (V)	Transfer Std Dev. %	Number of Readings	Uncertainty (%) (*k*=1)	Cumulative Burn Hrs
Trap-1	61.228	4.983	8.29	0.036	40	0.32	1.43
Trap-2	61.398	4.982	8.289	0.054	40	0.32	2.10
Trap-3	61.292	4.983	8.288	0.003	40	0.32	2.80
mean	**61.306**			**0.08**	**(ESDM % of 3 measurements)**		

Reference number of artefact (lamp): ETH3 Ambient temperature: 23 ± 2 ℃

Reference photometer	Test lamp Luminous Intensity (cd)	Lamp Current (A)	Lamp Voltage (V)	Transfer Std Dev. %	Number of Readings	Uncertainty (%) (*k*=1)	Cumulative Burn Hrs
Trap-2	77.29	5.931	8.835	0.057	40	0.32	2.15
Trap-1	77.191	5.931	8.838	0.023	40	0.32	2.90
Trap-3	77.262	5.931	8.838	0.025	40	0.32	3.57
mean	**77.248**			**0.04**	**(ESDM % of 3 measurements)**		

Reference number of artefact (photometer): LMT 039638 Ambient temperature: 23 ± 2 ℃

Reference photometer	Luminous Responsivity (nA/lx)	Illuminance level (lx)	Colour temp. of Source	Transfer Std Dev. %	No. of Readings	Uncertainty (%) (*k*=1)
Trap-1	38.696	44.426	2856	0.029	40	0.29
Trap-2	38.639	44.485	2856	0.002	40	0.29
Trap-3	38.616	44.44	2856	0.002	40	0.29
mean	**38.650**		**0.06**	**(ESDM % of 3 measurements)**		

A.2.3 Round 2 measurements at CSIRO

Table A.2.3 Results of individual measurements of lamp luminous intensities and photometer luminous responsivity during round 2 tests at the CSIRO laboratory

Reference number of artefact (lamp): ETH1 Ambient temperature: 21 ± 1 °C

Measurement Number	Luminous Intensity (cd)	Current (A)	Voltage (V)	Transfer Std Dev. %	Number of Readings	Uncertainty % (k=1)	Cumulative Burn Time (H)
1	71.112	5.935	8.822	0.0066	20	0.21	4.80
2	71.136	5.935	8.824	0.0253	20	0.21	5.10
3	71.150	5.935	8.825	0.0321	20	0.21	5.40
Mean	**71.133**	**5.935**	**8.824**	**0.016**	**(ESDM % of 3 measurements)**		

Reference number of artefact (lamp): ETH2 Ambient temperature: 21 ± 1 °C

Measurement Number	Luminous Intensity (cd)	Current (A)	Voltage (V)	Transfer Std Dev. %	Number of Readings	Uncertainty %	Cumulative Burn Time (H)
1	61.231	4.983	8.289	0.0139	20	0.21	3.10
2	61.159	4.983	8.289	0.0182	20	0.21	3.40
3	61.179	4.983	8.291	0.0386	20	0.21	3.75
Mean	**61.190**	**4.983**	**8.290**	**0.035**	**(ESDM % of 3 measurements)**		

Reference number of artefact (lamp): ETH3 Ambient temperature: 21 ± 1 °C

Measurement Number	Luminous Intensity (cd)	Current (A)	Voltage (V)	Transfer Std Dev. %	Number of Readings	Uncertainty %	Cumulative Burn Time (H)
1	77.194	5.931	8.824	0.0348	20	0.21	3.87
2	77.222	5.931	8.828	0.0255	20	0.21	4.17
3	77.179	5.931	8.826	0.0099	20	0.21	4.45
Mean	**77.198**	**5.931**	**8.826**	**0.016**	**(ESDM % of 3 measurements)**		

Reference number of artefact (photometer): LMT 039638 Ambient temperature: 21 ± 1 °C

Measurement Number	Luminous Responsivity nA / lx	Illuminance Level lx	Colour temp. of Source	Transfer Std Dev. %	Number Of Readings	Uncertainty %
1	38.611	45.195	2856	0.0089	40	0.20
2	38.619	44.318	2856	0.0113	40	0.20
3	38.624	45.343	2856	0.0121	40	0.20
Mean	**38.618**			**0.009**	**(ESDM % of 3 measurements)**	

A.3 Description of the measurement facility and traceability

A.3.1 CSIRO

Establishment of traceability route of the unit of luminous intensity including date of last realisation and breakdown of uncertainty:

A description of the method used to realise the laboratory unit of the candela in 1997 is given in part 7.1.

Laboratory reference standards used:

For the measurements of lamp luminous intensity:
Reference photometer LMT 039638.

For the measurements of photometer luminous response:
Laboratory reference lamps LIH20, LIH21, LIH22 and LIH23.

For all of the calibrations:

1. Reference detectors traceable to CSIRO's Cryogenic radiometer
2. Reference precision aperture traceable to CSIRO's length units
3. Distance scale on optical bench traceable to CSIRO's length units
4. Photometer picoammeter traceable to CSIRO's electrical current units
5. Lamp current shunt traceable to CSIRO's electrical resistance units
6. Lamp voltmeter units traceable to CSIRO's electrical potential units
7. Reference bolometers traceable to CSIRO's spectrophotometric units

For the measurements of the photometer luminous response or the luminous intensity of the lamps, which was measured using the same photometer, the photometer luminous response was measured by the use of four of the laboratory reference lamp standards of luminous intensity: LIH20, LIH21, LIH22 and LIH23. This procedure was repeated for each of the sets of measurements.

Description of measuring set-ups (including a diagram):

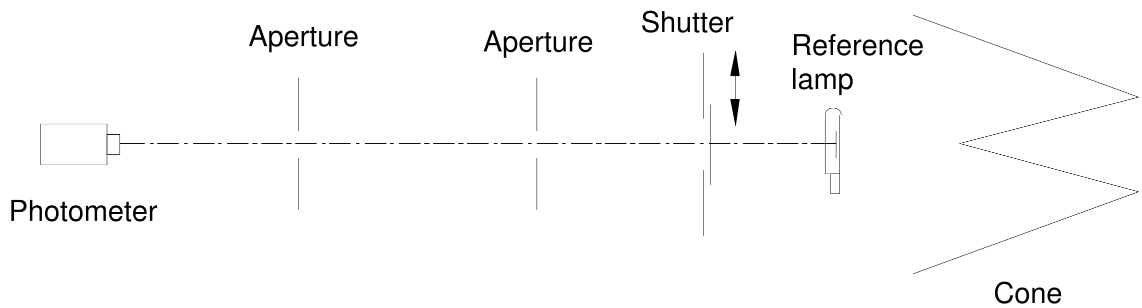

Figure A.3.1 The set-ups of both measurement for luminous intensity and luminous responsivity is as shown in the figure. The distance between the luminous intensity lamps and the detector calibration plane is fixed at 2.5m.

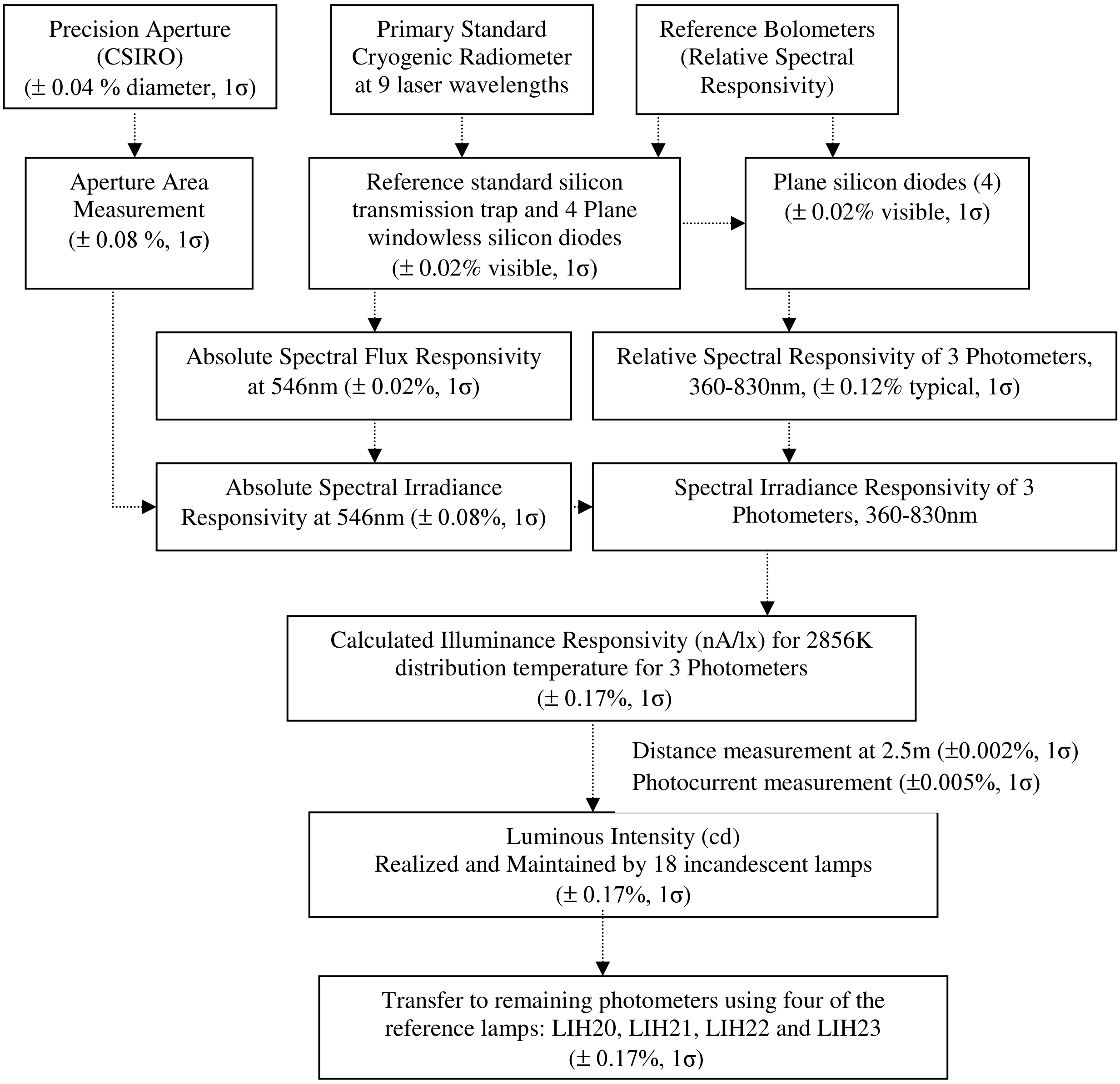

Figure A.3.2 Traceability chart for realising scales of luminous intensity and luminous response at CSIRO.

A.3.2 SPRING

Methods of realisation

The method used is discussed in part 7.2.

Traceability

Our new luminous intensity scale is essentially detector based and traceable to spectral responsivity scale based on a cryogenic radiometer, though the realisation also relies on the determination of the aperture area and spectral irradiance measurement for calculation of the spectral mismatch factor.

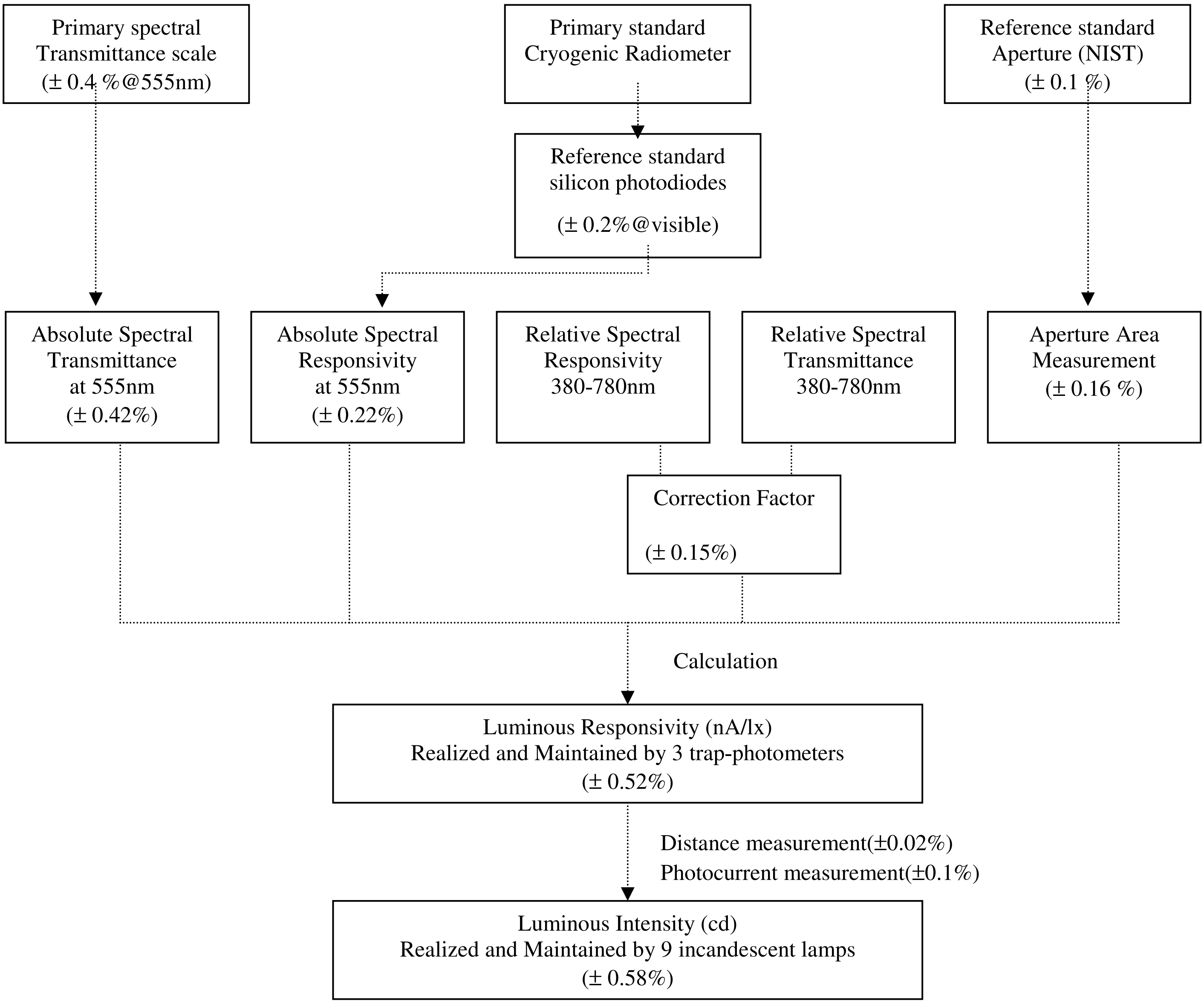

Figure A.3.3 Traceability chart for realisation of scales of luminous intensity and illuminance response at SPRING.

Laboratory reference standards used:

Reference detectors traceable to SPRING's Cryogenic radiometer
Spectrophotometer traceable to SPRING's transmittance scale
Reference standard aperture traceable to NIST's length scale
Distance scale on optical bench traceable to SPRING's Length scale
Electrometer traceable to SPRING's electric current measurement scale.

Description of measuring set-ups (please include a diagram):

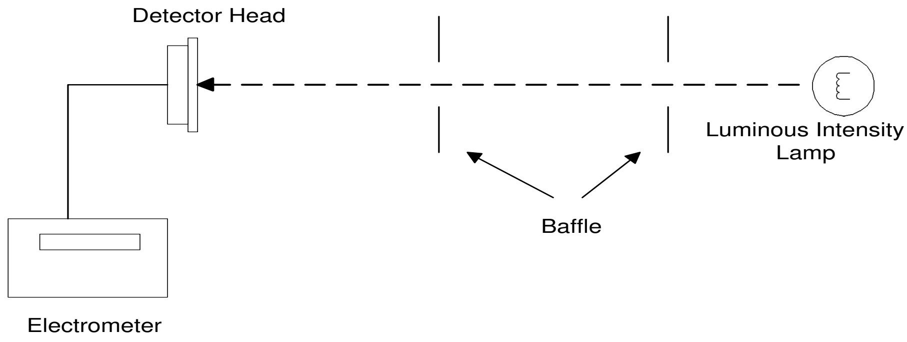

Figure A.3.4 The set-ups of both measurement for luminous intensity and luminous responsivity at SPRING is as shown in the figure. The distance between the luminous intensity lamps and the detector heads is fixed at 2.5m.

A.4 Record of lamp burn hours

Cumulative hours of burning of the intensity transfer lamps throughout the comparison are given in the tables in Appendix 2.

End of Report