Bilateral Comparison of Spectral Irradiance between NMIA (Australia) and SPRING (Singapore)

(KCDB reference No. CCPR-K1.a.1)

Final Report
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1. Introduction

The National Measurement Institute, Australia (NMIA, Australia, formerly CSIRO) and the Standards, Productivity and Innovation Board (SPRING Singapore) agreed in August 2003 to conduct a bilateral comparison on the spectral irradiance of tungsten halogen lamps covering the spectral region 250 nm to 1600 nm.

The aim of this bilateral comparison is to assess the equivalence of the spectral irradiance scales between the two laboratories and to link SPRING's spectral irradiance scale to the recent CIPM key comparison K1.a.

A technical protocol was produced that follows as closely as possible with the technical protocol used for the CIPM Key Comparison K1.a.

The comparison and its protocol were approved by CCPR and registered with KCDB with a comparison reference no. CCPR-K1.a.1.

NMIA acted as the pilot laboratory for this comparison

2. Organisation

2.1 Participants

Table 2.1

Address	Person in charge	Contact
NMIA - National Measurement Institute of Australia † PO Box 218, Lindfield, Australia	Dr. Mark Ballico (Frank Wilkinson)	Tel: +61-612-9413 7300 Fax: +61-612-9413 7202 E-mail: Frank.Wilkinson@measurement.gov.au
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† Note: NMIA previously known as the CSIRO National Measurement Laboratory.

2.2 Form of comparison

The comparison was principally carried out through the calibration of a group of travelling standard lamps prepared by NMIA. The full description of the lamps is given in section 3 of this report.

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

Most of the measurements were done over the period 11 November 2003 – 17 December 2003. Final round 2 measurements at NMIA of the relative spectral irradiances of the transfer lamps were done in August 2004.

3. Description of the lamps

The lamps are 1000W tungsten halogen lamps of the FEL type that has a double coiled tungsten filament supported at the top and bottom of the filament in a Bromine filled quartz envelop.

Each lamp was operated at a nominated direct current of approximately 8.7 amperes. The lamp was operated in constant current mode and the DC voltage of the power supply should be between 115 V and 120 V. The nominal operating colour temperature of the lamps under these conditions was 3200K.

The lamp was mounted on a large aluminium pillar that was fastened to a 3-pin kinematic base supported by a round brass base of a diameter 120 mm and height 25 mm. The optical axis defined at the centre of the lamp filament so realised was 270 mm above the bottom surface of the brass base.

Two electrical leads were soldered to the lamp pins at one end and connected to two large terminals at the other end for current and voltage connections. A photograph of the lamp mounted on the base is shown in Figure 3.1.

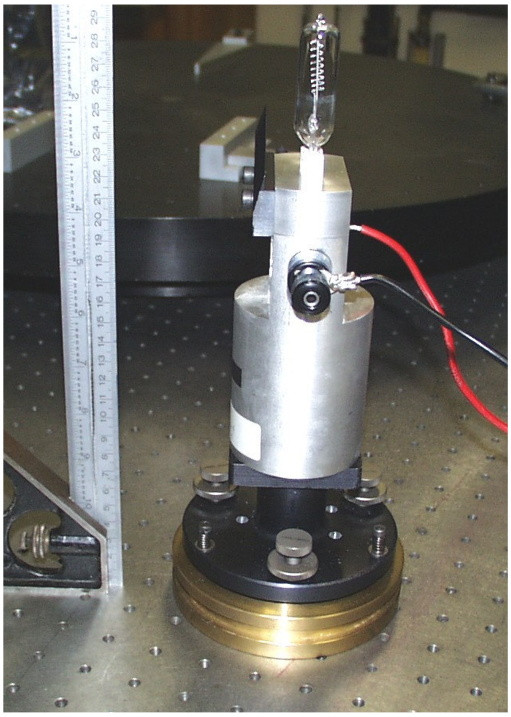

Figure 3.1 Transfer standard lamp with lamp support

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

4.2 Measurand

The measurand is the spectral irradiance of a lamp in a plane at the specified distance of 500.0 mm from a reference plane defined by the front surface of the shield mounted on the aluminium pillar in front of the lamp. The spectral irradiance should be measured for the defined operating current passing through the filament.

4.3 Alignment of the lamp and measurement instructions

Detailed instructions were provided in the protocol. From information provided these were closely followed by both of the laboratories.

5. Analysis of Results

Details of the measurement results are given in Appendix 2.

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

5.1 SPRING summary

Table 5.1 Mean spectral irradiances from 4 tests with the standard uncertainties

Wave-length nm	Spectral Irradiance W m⁻² nm⁻¹	Standard uncertainty %	Spectral Irradiance W m⁻² nm⁻¹	Standard uncertainty %	Spectral Irradiance W m⁻² nm⁻¹	Standard uncertainty %
	Lamp: **FEL1**		Lamp: **FEL5**		Lamp: **FEL6**	
250	2.773E-04	1.60	2.839E-04	1.60	2.660E-04	1.60
260	4.755E-04	1.57	4.872E-04	1.57	4.580E-04	1.57
270	7.724E-04	1.55	7.909E-04	1.55	7.464E-04	1.55
280	1.186E-03	1.52	1.186E-03	1.52	1.120E-03	1.52
290	1.763E-03	1.50	1.804E-03	1.50	1.711E-03	1.50
300	2.514E-03	1.38	2.581E-03	1.38	2.455E-03	1.38
310	3.528E-03	1.36	3.611E-03	1.36	3.436E-03	1.36
320	4.716E-03	1.34	4.842E-03	1.34	4.627E-03	1.34
330	6.217E-03	1.33	6.400E-03	1.33	6.120E-03	1.33
340	8.038E-03	1.32	8.280E-03	1.32	7.926E-03	1.32
350	1.018E-02	1.07	1.051E-02	1.07	1.008E-02	1.07
360	1.266E-02	1.06	1.307E-02	1.06	1.255E-02	1.06
370	1.552E-02	1.04	1.603E-02	1.04	1.541E-02	1.04
380	1.874E-02	1.03	1.937E-02	1.03	1.865E-02	1.03
390	2.232E-02	1.02	2.310E-02	1.02	2.225E-02	1.02
400	2.629E-02	0.93	2.721E-02	0.93	2.624E-02	0.93
450	5.088E-02	0.88	5.291E-02	0.88	5.121E-02	0.88
500	8.167E-02	0.85	8.503E-02	0.85	8.266E-02	0.85
550	1.146E-01	0.87	1.195E-01	0.87	1.166E-01	0.87
600	1.459E-01	0.80	1.521E-01	0.80	1.489E-01	0.80
650	1.734E-01	0.77	1.809E-01	0.77	1.775E-01	0.77
700	1.950E-01	0.76	2.035E-01	0.76	2.001E-01	0.76
750	2.109E-01	0.80	2.202E-01	0.80	2.169E-01	0.80
800	2.206E-01	0.74	2.306E-01	0.74	2.273E-01	0.74
850	2.251E-01	0.90	2.355E-01	0.90	2.323E-01	0.90
900	2.262E-01	0.84	2.383E-01	0.84	2.349E-01	0.84
950	2.230E-01	0.90	2.347E-01	0.90	2.316E-01	0.90
1000	2.175E-01	0.90	2.288E-01	0.90	2.259E-01	0.90
1100	2.016E-01	0.89	2.120E-01	0.89	2.097E-01	0.89
1200	1.816E-01	0.83	1.910E-01	0.83	1.892E-01	0.83
1300	1.608E-01	0.83	1.693E-01	0.83	1.679E-01	0.83
1400	1.406E-01	1.00	1.478E-01	1.00	1.466E-01	1.00
1500	1.225E-01	1.00	1.290E-01	1.00	1.280E-01	1.00
1600	1.074E-01	0.95	1.130E-01	0.95	1.123E-01	0.95

5.2 NMIA summary

Mean spectral irradiances from the two sets of three measurements made in rounds 1 and 2 have been calculated, with each measurement given equal weighting. The justification for this is discussed in part 5.4 below.

Table 5.2 Mean spectral irradiances from 4 – 6 tests from rounds 1 and 2 with standard uncertainties

Wave-length nm	Spectral Irradiance W m^{-2} nm^{-1}	Standard uncertainty %	Spectral Irradiance W m^{-2} nm^{-1}	Standard uncertainty %	Spectral Irradiance W m^{-2} nm^{-1}	Standard uncertainty %
	Lamp: **FEL1**		Lamp: **FEL5**		Lamp: **FEL6**	
250	0.000284	1.47	0.000289	1.47	0.00027	1.47
260	0.00048	0.86	0.00049	0.86	0.000461	0.86
270	0.000779	0.80	0.000796	0.80	0.000752	0.80
280	0.001194	0.74	0.001192	0.74	0.001127	0.74
290	0.001778	0.68	0.001819	0.68	0.001726	0.68
300	0.002536	0.63	0.002601	0.63	0.002476	0.63
310	0.003556	0.59	0.00364	0.59	0.003468	0.59
320	0.004751	0.56	0.004885	0.56	0.004664	0.56
330	0.006262	0.53	0.006449	0.53	0.006164	0.53
340	0.008087	0.50	0.008344	0.50	0.007983	0.50
350	0.010241	0.47	0.010575	0.47	0.010136	0.47
360	0.012749	0.45	0.013177	0.45	0.012646	0.45
370	0.015621	0.42	0.016154	0.42	0.015519	0.42
380	0.018863	0.40	0.019524	0.40	0.018782	0.40
390	0.022458	0.38	0.023264	0.38	0.022407	0.38
400	0.026428	0.36	0.027407	0.36	0.026418	0.36
450	0.05121	0.29	0.053257	0.29	0.051581	0.29
500	0.082039	0.26	0.085527	0.26	0.083142	0.26
550	0.114993	0.24	0.120118	0.24	0.117076	0.24
600	0.146372	0.25	0.153078	0.25	0.149578	0.25
650	0.173816	0.26	0.181994	0.26	0.17814	0.26
700	0.195621	0.29	0.205017	0.29	0.201081	0.29
750	0.21122	0.33	0.221548	0.33	0.217614	0.33
800	0.221154	0.36	0.232205	0.36	0.228379	0.36
850	0.225807	0.42	0.237032	0.42	0.233398	0.42
900	0.22625	0.45	0.237389	0.45	0.234183	0.45
950	0.223307	0.48	0.234474	0.48	0.231469	0.48
1000	0.217586	0.50	0.228624	0.50	0.225887	0.50
1100	0.200994	0.57	0.21133	0.57	0.208944	0.57
1200	0.181334	0.61	0.190887	0.61	0.188708	0.61
1300	0.160961	0.65	0.169329	0.65	0.167604	0.65
1400	0.141046	0.68	0.148498	0.68	0.147044	0.68
1500	0.123151	0.72	0.129726	0.72	0.128524	0.72
1600	0.10728	0.92	0.113077	0.92	0.111976	0.92

5.3 Comparison of results

The overall mean values of spectral irradiance measured for each lamp at SPRING have been divided by those measured at NMIA. The ratios are graphed in Fig 5.1 along with some of the combined uncertainties for the two laboratories.

Table 5.3 Comparison of mean spectral irradiances measured by SPRING with mean irradiances measured by NMIA in this bilateral comparison

Wave-length (nm)	Ratio: SPRING/ NMIA spectral irradiances for transfer lamp			Combined NMIA & SPRING standard uncertainties %
	FEL1	FEL5	FEL6	
250	0.9774	0.9824	0.9855	2.17
260	0.9897	0.9941	0.9931	1.79
270	0.9916	0.9934	0.9919	1.74
280	0.9937	0.9951	0.9939	1.70
290	0.9915	0.9917	0.9912	1.65
300	0.9914	0.9926	0.9915	1.52
310	0.9919	0.9919	0.9910	1.49
320	0.9925	0.9911	0.9920	1.46
330	0.9929	0.9925	0.9928	1.43
340	0.9940	0.9924	0.9928	1.41
350	0.9945	0.9938	0.9942	1.17
360	0.9931	0.9920	0.9924	1.15
370	0.9935	0.9924	0.9932	1.13
380	0.9934	0.9921	0.9928	1.11
390	0.9938	0.9928	0.9930	1.09
400	0.9946	0.9929	0.9932	1.00
450	0.9935	0.9935	0.9927	0.93
500	0.9955	0.9942	0.9941	0.88
550	0.9970	0.9946	0.9958	0.90
600	0.9970	0.9937	0.9954	0.83
650	0.9976	0.9943	0.9965	0.82
700	0.9966	0.9927	0.9950	0.81
750	0.9986	0.9938	0.9969	0.87
800	0.9974	0.9932	0.9953	0.83
850	0.9969	0.9934	0.9954	0.99
900	0.9998	1.0040	1.0031	0.95
950	0.9988	1.0009	1.0006	1.02
1000	0.9995	1.0006	1.0001	1.03
1100	1.0028	1.0030	1.0038	1.05
1200	1.0012	1.0007	1.0026	1.03
1300	0.9993	1.0000	1.0016	1.05
1400	0.9967	0.9952	0.9967	1.21
1500	0.9945	0.9940	0.9961	1.23
1600	1.0008	0.9993	1.0025	1.32

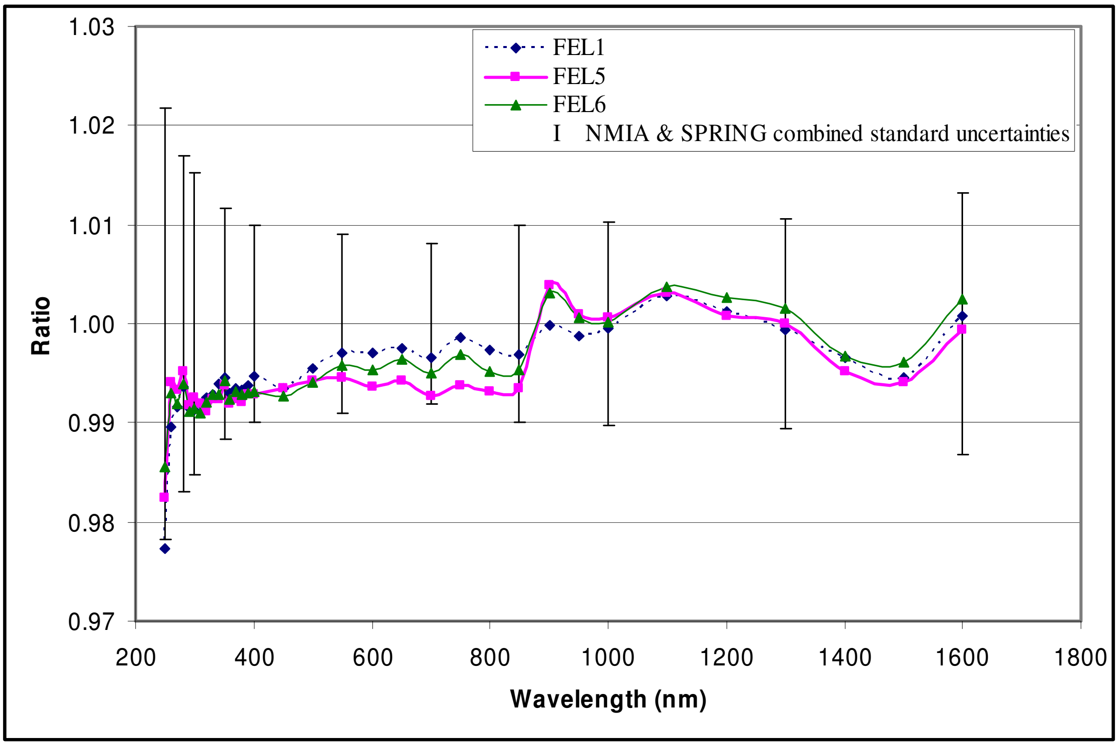

Figure 5.1 Ratios of spectral irradiances of three transfer lamps measured at SPRING to those measured at NMIA compared with combined standard uncertainties (k=1) for the two laboratories

5.4 Differences in methods between NMIA and SPRING

Before discussing the results it is worthwhile pointing out the differences in the methods used at each laboratory. At NMIA, each transfer lamp was initially compared with a different laboratory lamp standard of **relative** spectral irradiance. The transfer lamp illuminances were then measured three times with a photometer that had been calibrated using four laboratory lamp standards of illuminance. After returning from Singapore, each transfer lamp was compared with three different standards of relative spectral irradiance, only one of which had been used for the preliminary (round 1) measurements. Its illuminances were re-measured in the same manner as for round 1. Therefore, five of the six measurements of relative spectral irradiance came from different reference lamps for which the spectral irradiances were only about 50% correlated, but the illuminances and normalisation of all of the lamp relative irradiances were highly correlated.

At SPRING the absolute spectral irradiances were measured directly using a spectroradiometer that had been calibrated using four NIST spectral irradiance standard lamps. The measurement sequence reported involved measuring each transfer lamp relative to one of the NIST standards on the first day, each in a different order against a second NIST standard on the second day, and then each again in different orders against both of the remaining NIST standards on day 3. The object was to distribute any systematic errors due to system drift, changes in environment etc in a random way for the three lamps.

At each wavelength a mean value of the system response was calculated from the use of the four lamps, and then used to measure each of the three transfer lamps. Therefore, the reported values for the three transfer lamps are strongly correlated.

5.5 Consistency of measurements

The consistency of the measurements at both laboratories is largely demonstrated by the consistency in the ratios of the spectral values for the three lamps shown in Fig 5.1.

5.5.1 Consistency of tests at NMIA

Changes in the lamp calibration values measured by NMIA from round 1 to round 2 are shown in Fig 5.2. These include changes in calibrations through the use of different reference lamps.

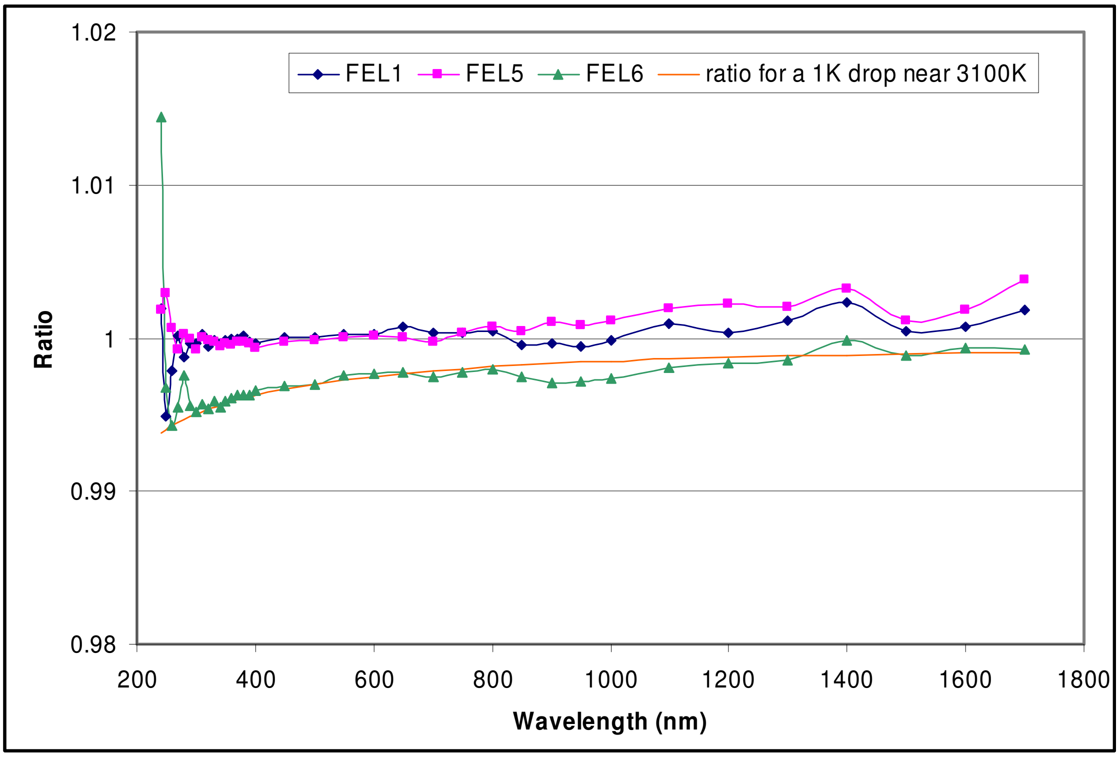

Figure 5.2 Ratio of spectral irradiances for given transfer lamp measured at NMIA in round 2 after return from Singapore to values initially measured in round 1. A curve representing a drop in filament temperature of about 1K is shown for comparison with the changes for lamp FEL6.

The differences in the calibrations obtained from different reference lamps used at NMIA are shown in Fig 5.3 for one of the lamps. They are similar for the other lamps. The differences appear to be due to systematic differences in the calibrations of the reference lamps from the high-temperature blackbody due to disparities in its calculated temperature and also different optical effects occurring during the blackbody to lamp transfers.

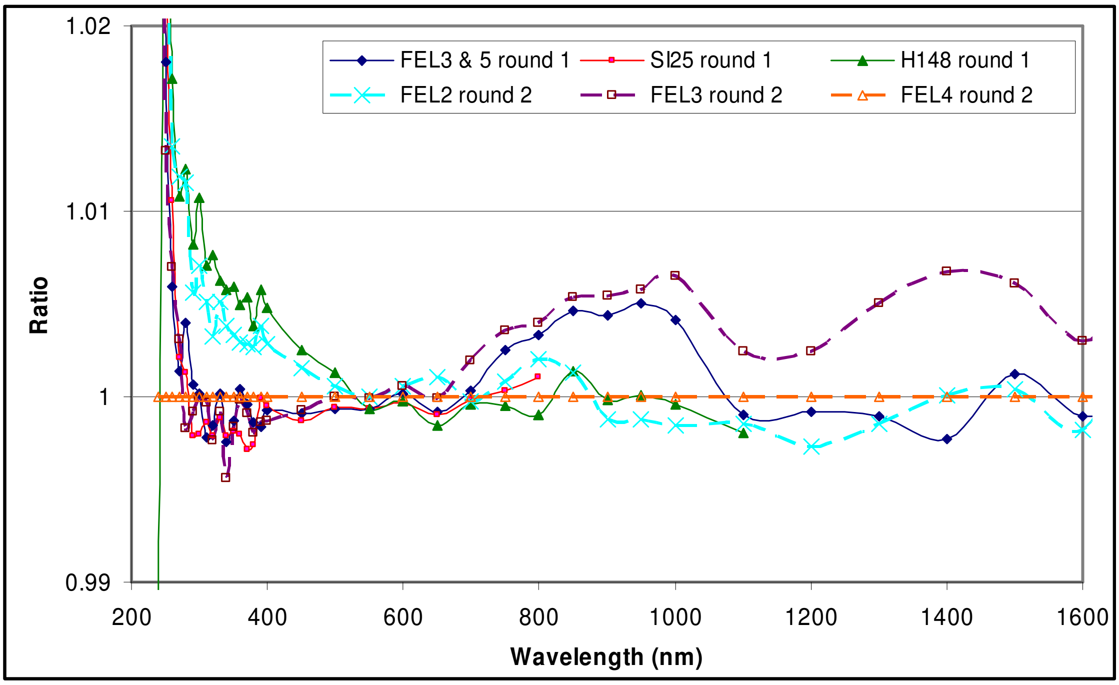

Figure 5.3 Ratios of spectral irradiances measured at NMIA using different reference standard lamps in both rounds of measurements to values measured from one of the references for the transfer lamp FEL1.

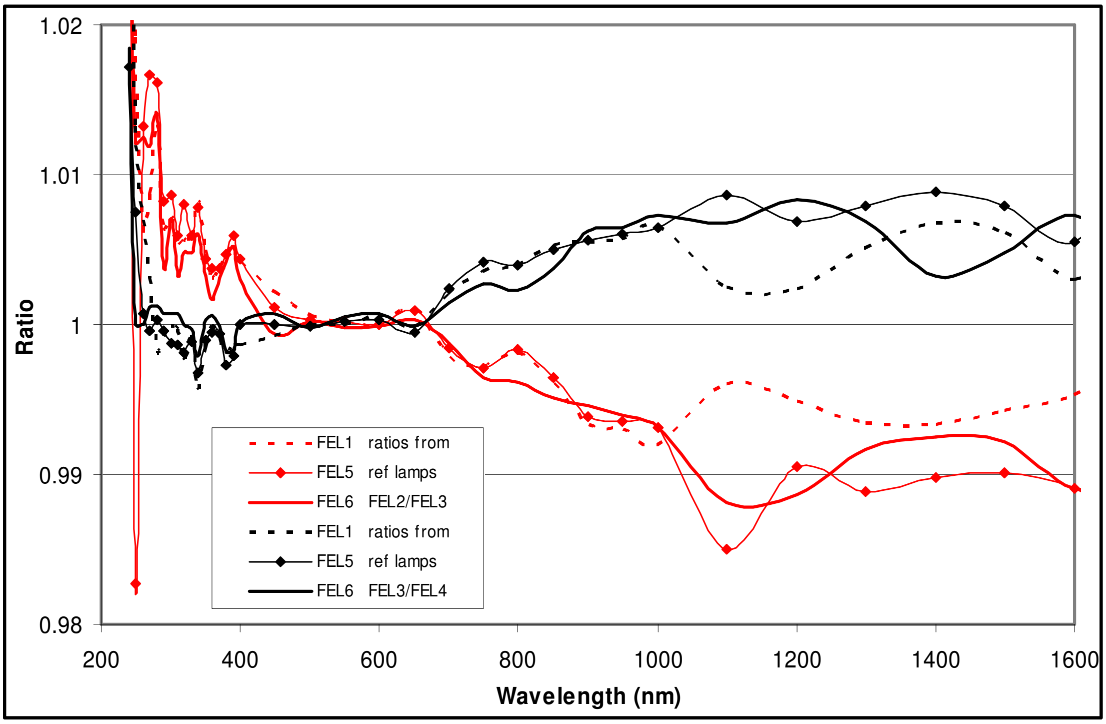

Figure 5.4 Ratios of spectral irradiances measured at NMIA from two different pairs of reference lamps for the three transfer lamps.

Figure 5.4 shows the consistency of the comparisons of the reference lamps and transfer lamps by showing the ratios of spectral irradiances obtained from different pairs of reference lamps for the three transfer lamps. Examining the ratios from both pairs of reference lamps, the range for the three transfer lamps only exceeds 0.3% twice over the 52 wavelengths between 280 nm and 1000 nm. At lower UV wavelengths the range is up to 3.6% at 250 nm and at IR wavelengths it is up to 1.1% at 1100 nm.

Transfers from other pairs of reference lamps show similar consistency. Therefore, the differences in calibration values for the transfer lamps shown in Fig 5.3 are considered to be due almost entirely to differences in the sizes of the spectral irradiance units carried by the reference lamps. Further examination of these shows that they are randomly distributed in value relative to the chosen reference (FEL4) between the two rounds of measurements. That is, there is no systematic trend in values between round 1 and round 2 for the lamp FEL1 represented here or for lamp FEL5. For lamp FEL6 there was a similar random distribution of ratios to the lamp FEL4 but with a separation of about 0.4% in absolute level between rounds 1 and 2 as also shown in Fig 5.2.

The standard deviations of the six sets of spectral irradiances for the three transfer lamps (Fig 5.3 representing lamp FEL1) have been compared with uncorrelated uncertainties that were calculated for similar calibrations of CCPR key comparison transfer lamps in November 2003 and are shown in Fig 5.5. The standard deviations are generally lower except for lamp FEL6 at the shorter wavelengths due to its apparent drop in output and temperature between the two rounds of tests.

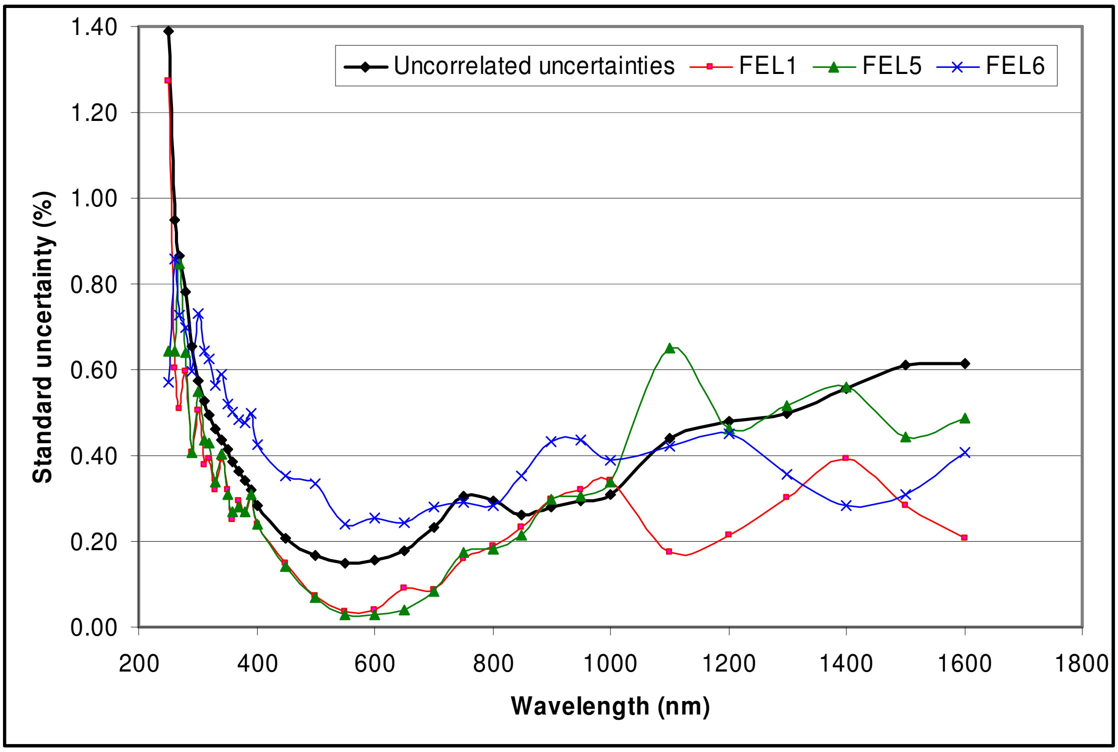

Figure 5.5 Comparison of estimated uncorrelated uncertainties in the spectral irradiances of the transfer lamps as adopted from tests done in November 2003 and the standard deviations of the six sets of calibrations done in rounds 1 and 2 of this bilateral comparison.

With these results it was decided that all NMIA test results were acceptable, to pool all measurement results from both rounds for each lamp treating them equally and to comparing the mean values with the results of the SPRING calibrations.

5.5.2 Consistency of measurements at SPRING

The SPRING spectroradiometer spectral response was calibrated using four separate reference lamps calibrated by NIST and the ratios of the responses relative to those obtained from the most recently acquired lamp, F538, are shown in Fig 5.6. The large differences at 1400 nm may be due to unsuspected differences in lamp envelope hydroxyl ion absorption, as spectral irradiance values at 1400 nm are not supplied by NIST and have been interpolated at SPRING. It could also be due to different atmospheric absorptions in different days of calibration.

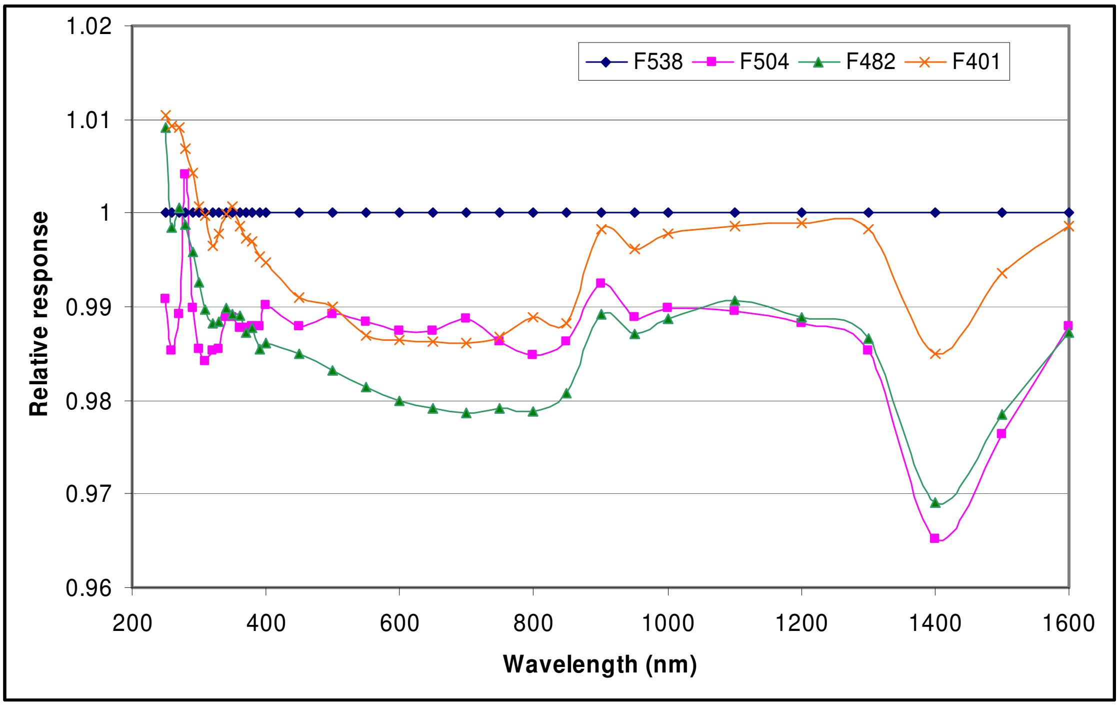

Figure 5.6 Ratios of spectroradiometer response at SPRING obtained from use of given NIST-calibrated spectral irradiance standard to responses from one of the standards, F538.

The ratios of the system response measured at the end of a day's calibrations to those measured at the start of the day using three of these reference standards are shown in Fig 5.7. The curves at the shorter wavelengths represent ratios obtained for the photomultiplier detector. These ratios have been plotted on a similar scale to the ratios shown in Fig 5.6 to support the conclusion that most of the differences shown in Fig 5.6 arise from differences in the reference lamp units – either due to the values given by NIST, subsequent changes in the lamps or a combination of the two.

From the four calibrations done on each transfer lamp at SPRING using a common set of system spectral responses, experimental standard deviation of mean values have been estimated and are shown in Fig 5.8. The maximum values of these have been used as transfer uncertainties in the uncertainty budget shown in Table 6.3.

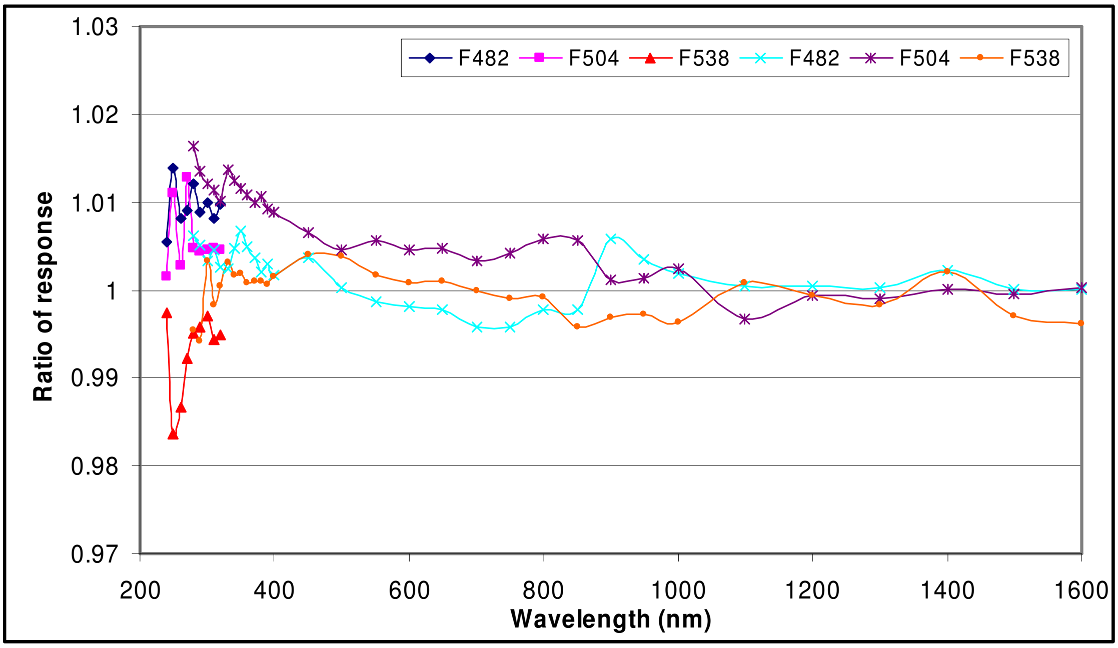

Figure 5.7 Ratios of spectroradiometer response at SPRING measured at the end of a day's tests to those measured at the start of the day using three of the reference lamps.

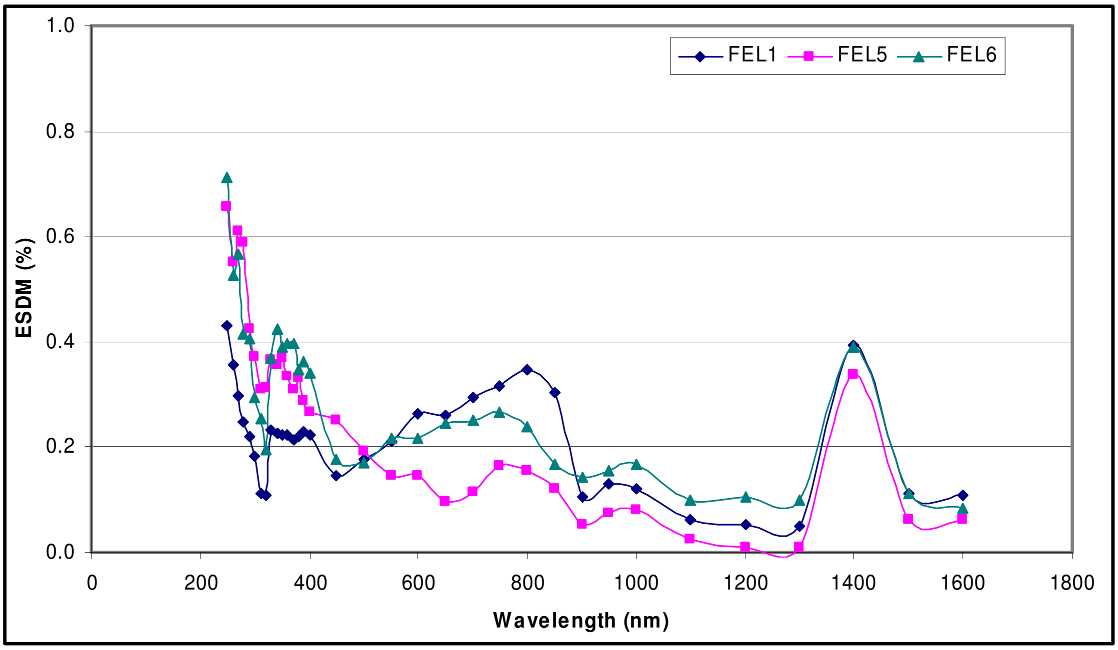

Figure 5.8 Experimental standard deviations of mean values from four tests at SPRING of the spectral irradiances of the transfer lamps FEL1, FEL5 and FEL6

Finally, the ratios of the SPRING and NMIA lamp spectral irradiances are compared with the combined transfer uncertainties and shown in Fig 5.9. The differences between the two laboratory scales are clearly greater and systematically so over much of the spectral range than the combined random uncertainties (k = 1).

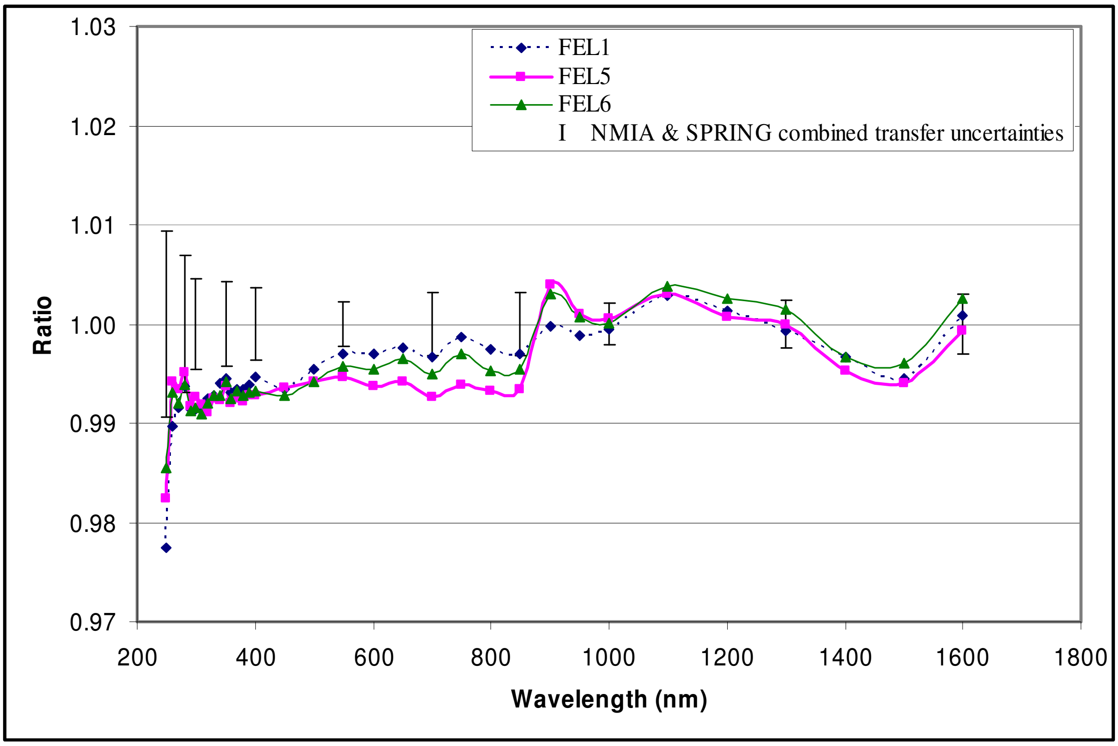

Figure 5.9 Comparison of ratios of SPRING and NMIA measured spectral irradiances with the combined laboratory transfer uncertainties.

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 NMIA uncertainties

Table 6.1 Standard uncertainties for calibration of the lamps FEL1, FEL5 and FEL6 at NMIA

Wave-length (nm)	No. of trans-fers (n)	NMIA scale		Test lamp			Trans-fers from n ref. lamps	Total uncertainty (%)	
		Correlated	Un-correlated						
		Between ref. lamps		Dist-ance	Current	Wave-length		Type A	Type A+B
Type:		B	A	B	B	B	A		
Note:	1	2	3	4	5	6	7		
250	5	1.324	0.494	0.08	0.12	0.01	0.38	0.62	1.47
260	5	0.734	0.388	0.08	0.111	0.01	0.17	0.42	0.86
270	5	0.688	0.358	0.08	0.103	0.01	0.15	0.39	0.80
280	5	0.645	0.329	0.08	0.096	0.01	0.12	0.35	0.74
290	5	0.605	0.290	0.08	0.09	0.01	0.04	0.29	0.68
300	5	0.569	0.256	0.08	0.083	0.01	0.03	0.26	0.63
310	5	0.535	0.233	0.08	0.077	0.01	0.03	0.24	0.59
320	5	0.503	0.219	0.08	0.072	0.01	0.03	0.22	0.56
330	5	0.474	0.206	0.08	0.067	0.01	0.02	0.21	0.53
340	5	0.448	0.193	0.08	0.062	0.01	0.03	0.20	0.50
350	5	0.423	0.182	0.08	0.057	0.01	0.03	0.18	0.47
360	5	0.400	0.171	0.08	0.053	0.01	0.03	0.17	0.45
370	5	0.379	0.161	0.08	0.049	0.01	0.03	0.16	0.42
380	5	0.359	0.152	0.08	0.045	0.01	0.02	0.15	0.40
390	5	0.341	0.143	0.08	0.041	0.01	0.01	0.14	0.38
400	5	0.325	0.126	0.08	0.038	0.01	0.02	0.13	0.36
450	5	0.263	0.092	0.08	0.023	0.01	0.01	0.09	0.29
500	5	0.230	0.073	0.08	0.011	0.01	0.02	0.08	0.26
550	5	0.220	0.066	0.08	0.001	0.01	0.01	0.07	0.24
600	5	0.225	0.069	0.08	0.007	0.01	0.01	0.07	0.25
650	5	0.238	0.077	0.08	0.014	0.01	0.02	0.08	0.26
700	5	0.254	0.104	0.08	0.02	0.01	0.01	0.10	0.29
750	5	0.288	0.136	0.08	0.025	0.01	0.01	0.14	0.33
800	5	0.323	0.131	0.08	0.03	0.01	0.02	0.13	0.36
850	4	0.386	0.129	0.08	0.034	0.01	0.01	0.13	0.42
900	4	0.416	0.139	0.08	0.038	0.01	0.02	0.14	0.45
950	4	0.444	0.147	0.08	0.041	0.01	0.02	0.15	0.48
1000	4	0.470	0.155	0.08	0.044	0.01	0.01	0.15	0.50
1100	4	0.516	0.219	0.08	0.049	0.01	0.01	0.22	0.57
1200	4	0.555	0.233	0.08	0.053	0.01	0.06	0.24	0.61
1300	4	0.588	0.244	0.08	0.056	0.01	0.05	0.25	0.65
1400	4	0.617	0.270	0.08	0.059	0.01	0.07	0.28	0.68
1500	4	0.641	0.294	0.08	0.062	0.01	0.08	0.31	0.72
1600	4	0.863	0.301	0.08	0.064	0.01	0.06	0.31	0.92

Notes:

1. The number of separate reference lamps used in the 4 – 6 calibrations in the two rounds from which the mean spectral irradiances have been calculated.
2. Uncertainties in blackbody temperature, stray light, illuminances scale etc common to all reference lamp calibrations.
3. Uncorrelated transfers from blackbody to reference lamps.
4. Uncertainty for an estimated 0.2 mm in 500 mm random distance uncertainty that includes possible filament movement.
5. 0.017% combined uncertainty in current for two lamps. Multiplying factor = 8 x (400/wavelength in nm).
6. Wavelength uncertainty is ~ 0.1 nm in UV-vis, ~ 0.2 nm in IR but errors are the same for both lamps. Wavelength reproducibility is ~ 0.02 nm.
7. Previously adopted single transfer uncertainty divided here by SQRT(number of different lamps used).

6.2 SPRING uncertainties

The uncertainty budgets of SPRING's spectral irradiance measurements at 250nm (in details) and all wavelengths (in summary form) are given in Table 6.2 and Table 6.3 respectively.

Table 6.2 Uncertainty budget of SPRING's spectral irradiance measurements at 250nm

$u(x_i)$	Source of Uncertainty	Type	Value of $u(x_i)$	C_i	Probability Distribution	k	$u_i(y)$ % relative	DoF
u(1)	Calibration uncertainty of the ref. Std.	B	1.82%	1	normal	2	0.91	∞
u(2)	Drift	B	1.64%	1	rectangular	1.73	0.95	∞
u(3)	Interpolation unc.	B	0.0%	1	rectangular	1.73	0.0	∞
u(4)	Stray light	B	0.5%	1	rectangular	1.73	0.29	∞
u(5)	Positioning	B	0.1%	2	rectangular	1.73	0.12	∞
u(6)	Wavelength setting	B	0.15nm	5.6 %/nm	rectangular	1.73	0.48	∞
u(7)	Current setting	B	0.02%	12	rectangular	1.73	0.14	∞
u(8)	Non-linearity	B	0.1%	1	rectangular	1.73	0.06	∞
u(9)	Reproducibility of transfer	A	0.7%	1	normal	1	0.7	3
$u_c(y)$	Combined uncertainty						1.6	

Notes:

1. $u(x_i)$ Uncertainty components;
2. c_i Sensitivity coefficient for the ith component; $c_i=(\partial f/\partial x_i)$
3. k Coverage factor, dependent on the type of distribution;
4. $u_i(y)$ Uncertainty contribution, $u_i(y) = c_i * u(x_i)/k$
5. $u_c(y)$ Combined uncertainty; $u_c(y) = \{\sum u_i^2(y)\}^{1/2}$
6. y Estimates (the mean) of the measurand of calibration
7. DoF Effective degrees of freedom
8. Drift of reference standard is calculated using data from NIST document Spectral Irradiance Calibration, NBS Special Publication 250-20, which provides drift rates of 4 NIST issued FEL standard lamps. The values used here is the average drift of 4 lamps with an average burning time of 50 hours, i.e. the average burning time of 4 SPRING reference standard lamps.
9. Interpolation of spectral irradiance values of the reference standard lamps at wavelength points not provided by NIST is carried out using NIST proposed methods which has a maximum uncertainty of 0.5%.
10. Stray light is assessed by several cut-off filters.
11. Positioning uncertainty is calculated for a distance setting uncertainty of 0.5 mm.
12. Wavelength setting induced uncertainty is calculated by $dE(\lambda)/E(\lambda) = (c_2/\lambda T-5)d\lambda/\lambda$ where $E(\lambda)$ is the spectral irradiance produced by a blackbody at a temperature T=3100K, c_2=0.014388mK is the second radiation constant and dλ is the wavelength uncertainty. The values of dλ are 0.15 nm from 250nm to 800nm and 0.6nm from 800nm to 1600nm
13. Current setting induced uncertainty is calculated using formula 5*(600/λ)*d(I). The value of 0.02% includes uncertainties from the standard resistor and the digital volt meter.
14. Reproducibility of transfer is the standard deviation of the mean of multiple calibrations done in different days with realignment of both reference standard lamps and the test lamps. The values used are the maximum values found in the wavelength range of 250-290nm, 300-390, 400-800 and 850-1600nm, respectively.

Table 6.3 Input uncertainties and combined uncertainty at each wavelength for measurements at SPRING (for key to input uncertainties see Table 6.2 above)

Wave-length (nm)	Input uncertainty									Total
	u(1)	u(2)	u(3)	u(4)	u(5)	u(6)	u(7)	u(8)	u(9)	$u_c(y)$
250	0.91	0.95	0.00	0.291	0.116	0.482	0.139	0.058	0.70	1.60
260	0.91	0.92	0.00	0.291	0.116	0.440	0.133	0.058	0.70	1.57
270	0.91	0.89	0.00	0.291	0.116	0.402	0.128	0.058	0.70	1.55
280	0.91	0.87	0.00	0.291	0.116	0.368	0.124	0.058	0.70	1.52
290	0.91	0.84	0.00	0.291	0.116	0.338	0.120	0.058	0.70	1.50
300	0.91	0.82	0.00	0.150	0.116	0.311	0.116	0.058	0.50	1.38
310	0.91	0.80	0.00	0.150	0.116	0.287	0.112	0.058	0.50	1.36
320	0.91	0.78	0.00	0.150	0.116	0.265	0.108	0.058	0.50	1.34
330	0.91	0.76	0.00	0.150	0.116	0.245	0.105	0.058	0.50	1.33
340	0.91	0.74	0.00	0.150	0.116	0.227	0.102	0.058	0.50	1.32
350	0.55	0.73	0.00	0.017	0.116	0.211	0.099	0.058	0.50	1.07
360	0.55	0.71	0.00	0.017	0.116	0.196	0.096	0.058	0.50	1.06
370	0.55	0.70	0.00	0.017	0.116	0.182	0.094	0.058	0.50	1.04
380	0.55	0.68	0.00	0.017	0.116	0.170	0.091	0.058	0.50	1.03
390	0.55	0.67	0.00	0.017	0.116	0.158	0.089	0.058	0.50	1.02
400	0.55	0.65	0.00	0.017	0.116	0.148	0.087	0.058	0.30	0.93
450	0.55	0.60	0.00	0.017	0.116	0.106	0.077	0.058	0.30	0.88
500	0.55	0.55	0.00	0.017	0.116	0.077	0.069	0.058	0.30	0.85
550	0.55	0.51	0.29	0.017	0.116	0.057	0.063	0.058	0.30	0.87
600	0.55	0.48	0.00	0.017	0.116	0.042	0.058	0.058	0.30	0.80
650	0.46	0.45	0.29	0.017	0.116	0.030	0.053	0.058	0.30	0.77
700	0.54	0.42	0.00	0.059	0.116	0.022	0.050	0.058	0.30	0.76
750	0.54	0.40	0.29	0.059	0.116	0.015	0.046	0.058	0.30	0.80
800	0.54	0.38	0.00	0.059	0.116	0.010	0.043	0.058	0.30	0.74
850	0.54	0.36	0.29	0.173	0.116	0.023	0.041	0.058	0.50	0.90
900	0.54	0.35	0.00	0.173	0.116	0.010	0.039	0.058	0.50	0.84
950	0.57	0.33	0.29	0.173	0.116	0.001	0.037	0.058	0.50	0.90
1000	0.57	0.32	0.29	0.173	0.116	0.009	0.035	0.058	0.50	0.90
1100	0.57	0.29	0.29	0.173	0.116	0.022	0.032	0.058	0.50	0.89
1200	0.57	0.28	0.00	0.173	0.116	0.031	0.029	0.058	0.50	0.83
1300	0.57	0.26	0.00	0.173	0.116	0.036	0.027	0.058	0.50	0.83
1400	0.71	0.24	0.29	0.289	0.116	0.040	0.025	0.058	0.50	1.00
1500	0.71	0.23	0.29	0.289	0.116	0.043	0.023	0.058	0.50	1.00
1600	0.71	0.22	0.00	0.289	0.116	0.044	0.022	0.058	0.50	0.95

7. Summaries of measurement traceability and procedures

7.1 NMIA measurement scale

The NMIA scale of spectral irradiance that was used here is based on the new NML2003 scale of relative spectral irradiance combined with the NML1997 unit of illuminances. Filter radiometry traceable to a cryogenic radiometer was used to measure the thermodynamic temperatures of a high-temperature graphite blackbody. The relative spectral irradiances of tungsten halogen reference lamps were compared with those of the blackbody as calculated from its temperature using the Planck radiation equation. These relative spectral irradiances were then normalised to absolute spectral irradiance units by calculations based on the lamp's measured illuminance at the required position.

These reference lamps are of the same type as those used as transfer lamps in this bilateral comparison, so any uncertainties in the calibrations of the transfer lamps additional to those estimated for the reference lamps are dominated by the instability and reproducibility of both sets of lamps.

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

7.2 SPRING measurement scale

The SPRING spectral irradiance scale is based on the mean units equally obtained from four NIST-calibrated standard lamps, three of which were calibrated by NIST (NBS) prior to 2001 and one of which was calibrated in late 2001 after NIST adopted a new detector-based scale[4]. It therefore represents a mixture of the old and new NIST scale in the proportions of 3:1. These NIST-calibrated standards are of a similar type to that of the transfer lamps. The uncertainties in the calibrations of the reference standards, in their subsequent drift and in the reproducibility of the transfer lamps dominate the uncertainties.

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

8. Discussion

Since this comparison was carried out the results of the latest CIPM K1.a key comparison of spectral irradiances, conducted mainly in the period 2002-3, have been published[5]. As this bilateral comparison between NMIA and SPRING is essentially between the current NMIA scale and that obtained by SPRING from NIST it is interesting to compare the ratios of these with the ratios of the units obtained by NMIA and NIST in the key comparison. These two sets of ratios are compared in Fig 8.1 along with representative 95% combined uncertainty bars that were calculated for the key comparison.

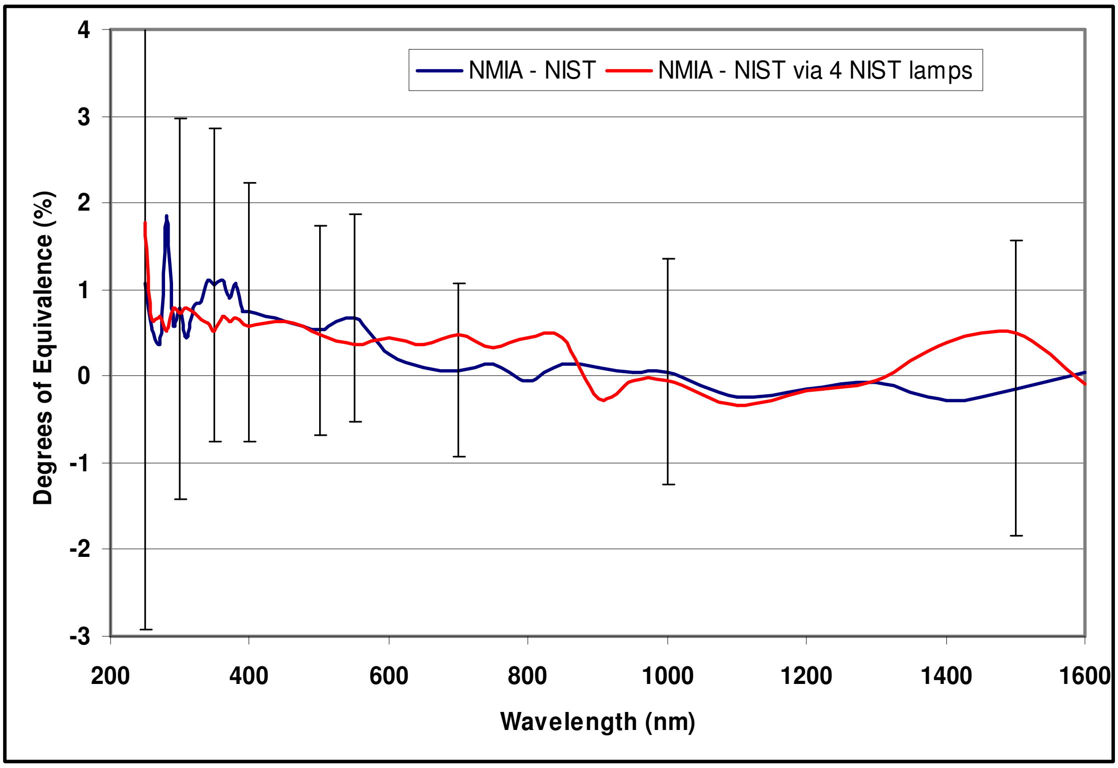

Figure 8.1 Degrees of equivalence (fractional difference, %) of NMIA – NIST spectral irradiance units derived from two different comparisons. The dark blue curve is derived from results of the 2002-2003 CCPR-K1.a key comparison together with some 95% confidence combined uncertainty bars for that key comparison, and the red curve is derived from results of the current comparison between NMIA and SPRING units where the latter were based on four lamps calibrated at different times by NIST.

The differences shown in Fig 8.1 are well within the expanded (95%) combined uncertainties for just one of the comparisons at all wavelengths, even within the combined standard uncertainties. There is therefore consistent agreement between the latest NIST scale and that obtained by SPRING via these four lamps as determined by this three-way comparison.

9. Link with CCPR KCRV values

9.1 The SPRING Degrees of Equivalence

Both NMIA and NIST took part in the latest CCPR-K1.a key comparison of spectral irradiances, the main part of which was conducted in 2002 and 2003. The "degrees of equivalence" or the unilateral differences between the laboratory's units and the key comparison reference values (KCRVs) have now been published[5] and these are shown in Fig 9.1 for the wavelength range covered by this bilateral comparison for both laboratories.

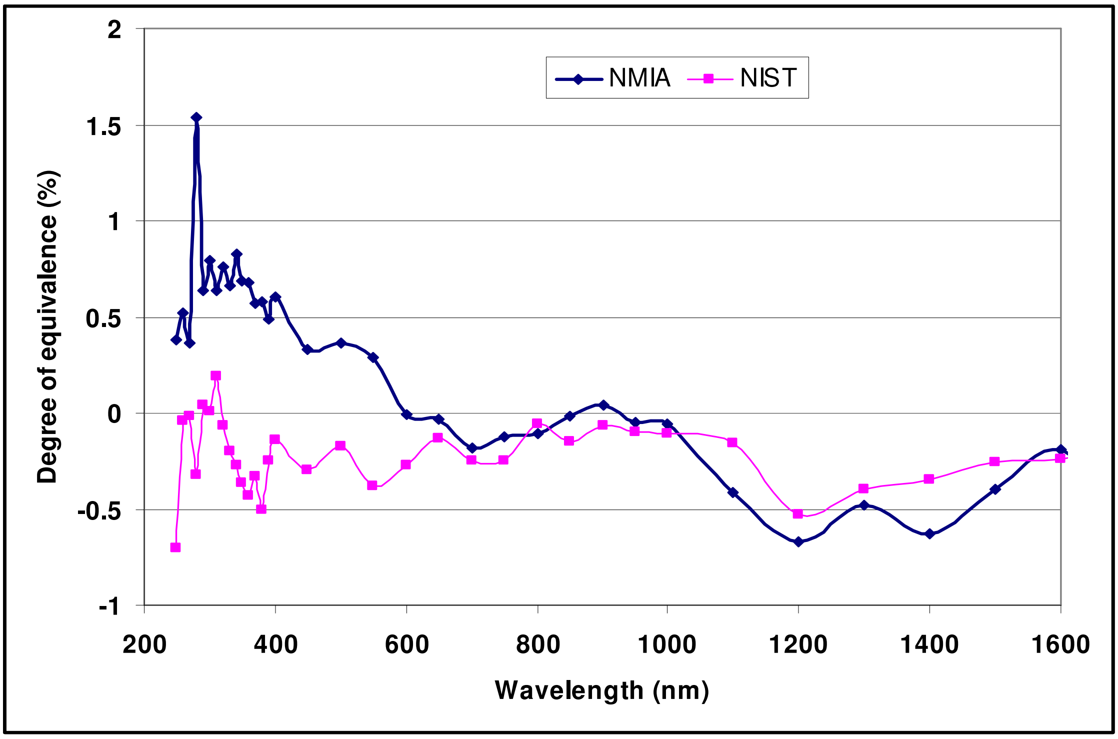

Figure 9.1 Degrees of equivalence (%) of the NMIA and the NIST spectral irradiance units to the KCRVs as given in final report of the CCPR-K1.a key comparison, March 2005.

The mean values of the % differences between the SPRING and the NMIA units from the three lamps, as shown in a ratio form in Fig 5.1, at each wavelength, are given in Table 9.1 together with the degrees of equivalence or % differences between the NMIA and KCRVs from the key comparison. From these, the degrees of equivalence or % differences between the SPRING spectral irradiance units and the KCRVs are calculated and are also given in the table. They are also given graphically in Fig 9.2.

Table 9.1 Degrees of equivalence (laboratory unit – KCRV) of NMIA and SPRING laboratories

Wavelength (nm)	NMIA-KCRV %	NMIA/SPRING ratio	SPRING-NMIA %	SPRING-KCRV %
250	0.38	1.0177	-1.77	-1.39
260	0.52	1.0066	-0.66	-0.14
270	0.36	1.0069	-0.69	-0.33
280	1.54	1.0052	-0.52	1.02
290	0.64	1.0078	-0.78	-0.14
300	0.79	1.0073	-0.73	0.06
310	0.64	1.0078	-0.78	-0.14
320	0.76	1.0073	-0.73	0.03
330	0.66	1.0066	-0.66	0.00
340	0.83	1.0061	-0.61	0.22
350	0.69	1.0051	-0.51	0.18
360	0.68	1.0068	-0.68	0.00
370	0.57	1.0063	-0.63	-0.06
380	0.58	1.0067	-0.67	-0.09
390	0.49	1.0061	-0.61	-0.12

(continued)

Table 9.1 (continued) Degrees of equivalence (laboratory unit – KCRV) of NMIA and SPRING laboratories

Wavelength (nm)	NMIA-KCRV %	NMIA/SPRING ratio	SPRING-NMIA %	SPRING-KCRV %
400	0.6	1.0057	-0.57	0.03
450	0.33	1.0063	-0.63	-0.30
500	0.36	1.0049	-0.49	-0.13
550	0.29	1.0037	-0.37	-0.08
600	-0.01	1.0044	-0.44	-0.45
650	-0.03	1.0037	-0.37	-0.40
700	-0.18	1.0049	-0.49	-0.67
750	-0.12	1.0032	-0.32	-0.44
800	-0.11	1.0045	-0.45	-0.56
850	-0.02	1.0045	-0.45	-0.47
900	0.04	0.9974	0.26	0.30
950	-0.05	0.9996	0.04	-0.01
1000	-0.06	0.9996	0.04	-0.02
1100	-0.41	0.9966	0.34	-0.07
1200	-0.67	0.9983	0.17	-0.50
1300	-0.48	0.9996	0.04	-0.44
1400	-0.63	1.0038	-0.38	-1.01
1500	-0.4	1.0050	-0.50	-0.90
1600	-0.19	0.9990	0.10	-0.09

9.2 Uncertainties in the SPRING Degrees of Equivalence

The NMIA units that have been used in both the CCPR key comparison of 2002-3 and this current bilateral comparison are strongly correlated by the common uncertainties in the base units. The uncertainties in the SPRING degrees of equivalence to the KCRV values are calculated from the quadratic sums of the SPRING uncertainties calculated for the bilateral comparison (including the uncertainties associated with the SPRING's base unit and the transfer measurement), and the total of the uncorrelated components of the NMIA uncertainties calculated for both the CCPR-K1.a key comparison and the current bilateral comparison.

The SPRING uncertainty (at each wavelength) of the base unit is the sum of the component uncertainties identified as u(1) to u(3) in Table 6.3 above. The SPRING uncertainty of transfer measurement is the sum of the component uncertainties in the calibration of one transfer lamp (the same uncertainty is claimed for any one of transfer lamps) identified as u(4) to u(9) in Table 6.3. The NMIA uncorrelated uncertainty for the key comparison CCPR-K1.a takes the value of the total Type A uncertainty given in the Table 6-5 of the Final Report of the comparison published in KCDB website. The NMIA uncorrelated uncertainty for the bilateral comparison takes the value of the uncertainty in the calibration of the transfer lamp relative to the NMIA unit. It includes uncertainties resulting from lamp current, distance and orientation uncertainties, from wavelength uncertainty and from transfer noise. The uncertainty contribution due to the possible drift of NMIA scale is considered negligible because the current comparison was conducted immediately after the CCPR-K1.a key comparison. In fact the second round of NMIA measurement for CCPR-K1.a and the first round of NMIA measurement for current comparison were both conducted in November 2003.

These uncertainties and the total standard uncertainties of the SPRING degrees of equivalence are given in Table 9.2.

Table 9.2 Standard uncertainties (%, k=1) of the SPRING Degrees of Equivalence to the KCRVs of the CCPR-K1.a key comparison held in the period 2002-2003

	Uncorrelated uncertainties in				SPRING-KCRV Total uncertainty
Wavelength (nm)	SPRING base unit unc.	SPRING unit transfer to lamp	NMIA unit transfer to lamp	NMIA transfer for CCPR-K1.a	in degrees of equivalence
250	1.31	0.92	0.86	0.846	2.01
260	1.29	0.90	0.42	0.394	1.67
270	1.27	0.88	0.36	0.337	1.62
280	1.26	0.86	0.31	0.489	1.63
290	1.24	0.85	0.18	0.281	1.54
300	1.23	0.63	0.16	0.124	1.39
310	1.21	0.62	0.16	0.100	1.37
320	1.20	0.61	0.16	0.108	1.36
330	1.19	0.60	0.14	0.088	1.34
340	1.18	0.59	0.15	0.108	1.33
350	0.91	0.57	0.15	0.110	1.09
360	0.90	0.56	0.15	0.102	1.07
370	0.88	0.56	0.14	0.099	1.06
380	0.87	0.55	0.14	0.092	1.05
390	0.86	0.55	0.13	0.085	1.03
400	0.85	0.37	0.13	0.095	0.94
450	0.81	0.35	0.12	0.087	0.89
500	0.77	0.34	0.12	0.091	0.86
550	0.80	0.34	0.12	0.082	0.88
600	0.72	0.33	0.12	0.081	0.81
650	0.70	0.33	0.12	0.091	0.79
700	0.68	0.34	0.12	0.083	0.78
750	0.73	0.34	0.12	0.085	0.82
800	0.66	0.33	0.12	0.088	0.76
850	0.71	0.55	0.12	0.085	0.91
900	0.64	0.55	0.13	0.091	0.86
950	0.72	0.55	0.13	0.089	0.91
1000	0.71	0.55	0.12	0.081	0.91
1100	0.70	0.55	0.13	0.085	0.90
1200	0.63	0.55	0.17	0.138	0.86
1300	0.62	0.55	0.16	0.130	0.85
1400	0.80	0.59	0.19	0.157	1.03
1500	0.80	0.59	0.21	0.186	1.04
1600	0.74	0.59	0.18	0.149	0.98

The standard uncertainties of the SPRING degrees of equivalence to the KCRVs are given as uncertainty bars at selected wavelengths together with the degrees of equivalence in Fig 9.2.

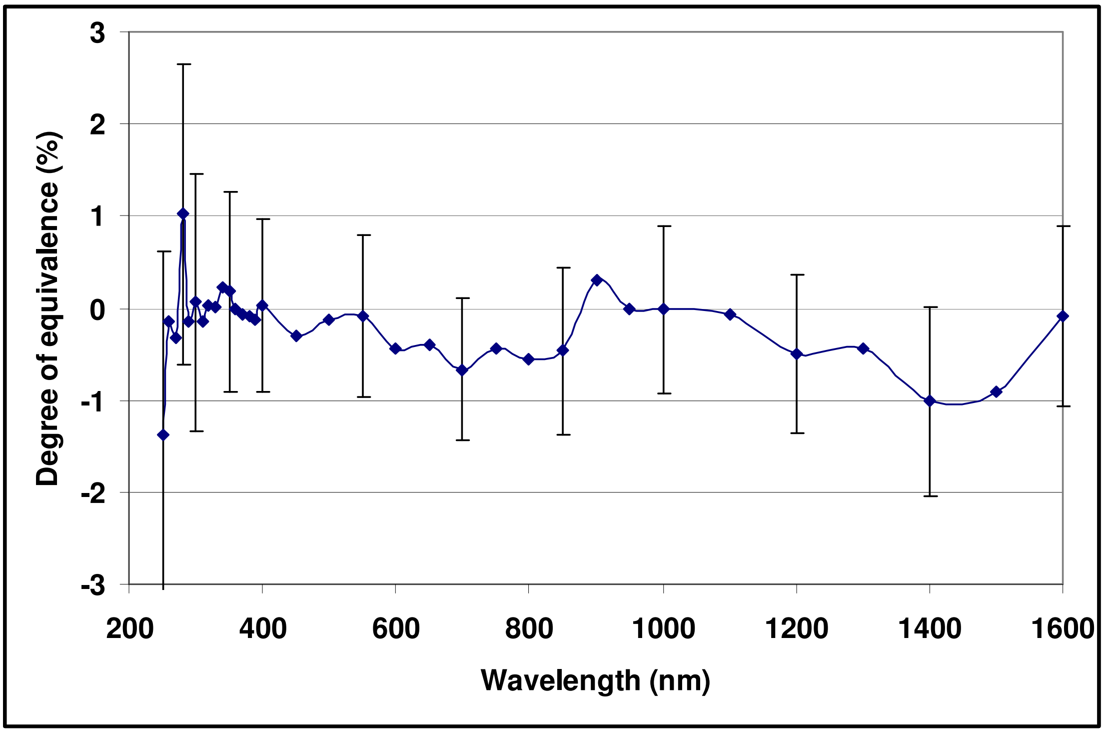

Figure 9.2 SPRING Degrees of Equivalence to the KCRVs of the 2002-2003 CIPM-K1.a key comparison of spectral irradiances shown with standard uncertainties (k=1) at selected wavelengths.

10. Conclusions

The spectral irradiance units measured by the SPRING and NMIA laboratories in this comparison are in agreement within the combined standard uncertainties of the laboratories over the wavelength range used in this comparison, 250 – 1600 nm.

There appear to be systematic differences between the two scales which is close to differences between the NMIA scale and the two NIST scales as represented by the group of reference lamps used at SPRING.

The consistency of the measurements at both SPRING and NMIA resulted in random uncertainties for transfers between the similar types of reference and transfer lamps which were considerably less than the calculated scale differences.

The choice of transfer lamps and their method of transport and handling resulted in only a relatively small drift in one of the lamps and so in a successful comparison.

For the use of the group of four reference lamps at SPRING on which this comparison was based, it is considered that the levels of uncertainty that have been submitted are appropriate.

11. References

1. F. Wilkinson, "Basis of NML2003 scale of relative spectral irradiance", Technical Report NMI TR1, National Measurement Institute, Lindfield, NSW Australia, December 2004.
2. J. L. Gardner, D. J. Butler, E. G. Atkinson and F. J. Wilkinson, "New basis for the Australian realization of the candela" Metrologia 35, 235-239(1998).
3. F Wilkinson, "The NML units of spectral responsivity 240 – 1650 nm", CSIRO Technical Memorandum TIPP 253, March 1998.
4. Yoon HW, Gibson CE and Barnes PY, "Realization of the National Institute of Standards and Technology detector-based spectral irradiance scale", Applied Optics **41**, 5879-5890, October 2002.
5. Woolliams E, Fox N, Cox M and Harris P, CIPM Key Comparison K1.a "Spectral Irradiance 250 nm to 2500 nm", Final Report, January 2006, published in the KCDB website.

A. Appendices

A.1 Analysis of uncertainties

In order to achieve optimum comparability, a list containing the principal influence parameters for calibration of spectral irradiance 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 lamp – this is the uncertainty due to the positioning and alignment of the lamp.

Uncertainty of the transfer measurement – this is the uncertainty involved in the transfer measurement of the lamp. 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

A.2.1 NMIA round 1 results

All measurements were done within the period 20 – 26 November 2003. Minimum number of measurements made at each wavelength from which the transfer standard deviation is calculated = 50. The cumulative lamp burn times are from the start of the round 1 measurements at NMIA. Ambient temperature for each test was 21ºC.

Table A.2.1 Spectral irradiances measured from 3 runs for lamp FEL1.

Wavelength nm	Cumulative lamp burn time at end of test					
	1.0 h		4.0 h		6.0 h	
	Spectral Irradiance W m^{-2} nm^{-1}	Transfer Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Transfer Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Transfer Std Dev. %
Spectral bandwidth: 2 nm						
250	0.000283	3.13	0.000285	5.08	0.000288	3.76
260	0.000479	0.94	0.000481	1.44	0.000484	1.09
270	0.000776	0.36	0.000777	0.51	0.000784	0.40
280	0.001193	0.18	0.00119	0.24	0.001203	0.20
290	0.001776	0.10	0.001771	0.14	0.001789	0.12
300	0.00253	0.07	0.002525	0.10	0.002557	0.08
310	0.003544	0.05	0.003547	0.07	0.003577	0.06
320	0.00474	0.04	0.004738	0.05	0.004784	0.05
330	0.006253	0.03	0.006245	0.04	0.006291	0.03
340	0.008067	0.02	0.008069	0.03	0.008133	0.03
350	0.01022	0.02	0.010214	0.03	0.010295	0.03
360	0.012742	0.02	0.01271	0.03	0.0128	0.02
370	0.015603	0.02	0.015566	0.02	0.015694	0.02
380	0.018835	0.01	0.018812	0.02	0.018934	0.02
390	0.022398	0.01	0.022432	0.02	0.022563	0.01
400	0.026386	0.01	0.026393	0.01	0.026532	0.01
450	0.051154	0.01	0.051135	0.01	0.051329	0.01
500	0.081978	0.01	0.081985	0.01	0.082136	0.01
550	0.114955	0.01	0.114955	0.01	0.114955	0.01
600	0.146375	0.01	0.146309	0.01	0.146316	0.01
650	0.173742	0.01	0.173713	0.02	0.173613	0.01
700	0.195631	0.01	0.195542	0.02	0.195495	0.02
750	0.211522	0.01	0.211059	0.01	0.210875	0.01
800	0.221535	0.01	0.221043	0.02	0.220591	0.01
850	0.226286	0.01			0.225548	0.01
900	0.226853	0.01			0.225827	0.01
950	0.223996	0.01			0.222899	0.01
1000	0.21811	0.01			0.217122	0.01
1100	0.200872	0.02			0.200677	0.02
Spectral bandwidth: 8 nm						
1200	0.181237	0.01				
1300	0.160687	0.00				
1400	0.140563	0.01				
1500	0.12306	0.01				
1600	0.107164	0.01				

Table A.2.2 Spectral irradiances measured from 3 runs for lamp FEL5.

Wavelength nm	Cumulative lamp burn time at end of test: 2.0 h		3.5 h		9.0 h	
	Spectral Irradiance W m⁻² nm⁻¹	Transfer Std Dev. %	Spectral Irradiance W m⁻² nm⁻¹	Transfer Std Dev. %	Spectral Irradiance W m⁻² nm⁻¹	Transfer Std Dev. %
Spectral bandwidth: 2 nm						
250	0.000288	3.04	0.000161	4.75	0.000157	3.84
260	0.000488	0.92	0.000288	1.35	0.000288	1.12
270	0.000792	0.35	0.000488	0.48	0.000493	0.41
280	0.001189	0.17	0.000793	0.22	0.000805	0.20
290	0.001815	0.10	0.001189	0.14	0.001197	0.12
300	0.002597	0.07	0.001814	0.10	0.001828	0.07
310	0.00363	0.05	0.002587	0.07	0.002623	0.05
320	0.004878	0.04	0.003625	0.05	0.003666	0.05
330	0.006437	0.03	0.004865	0.04	0.004916	0.03
340	0.00832	0.03	0.006431	0.03	0.006482	0.03
350	0.010562	0.02	0.008328	0.03	0.008396	0.02
360	0.013168	0.02	0.010545	0.02	0.01063	0.02
370	0.016143	0.01	0.013144	0.02	0.013237	0.02
380	0.019504	0.02	0.016102	0.02	0.016227	0.02
390	0.023211	0.01	0.019477	0.02	0.019606	0.02
400	0.027381	0.01	0.023229	0.02	0.023373	0.01
450	0.053242	0.01	0.027386	0.01	0.027507	0.01
500	0.085522	0.01	0.053175	0.01	0.053394	0.01
550	0.120089	0.01	0.085454	0.01	0.085634	0.01
600	0.153096	0.01	0.120089	0.01	0.120089	0.01
650	0.182057	0.01	0.153006	0.01	0.153045	0.01
700	0.20513	0.10	0.182001	0.02	0.181903	0.01
750	0.221442	0.10	0.205085	0.01	0.204994	0.01
Spectral bandwidth: 5 nm						
800	0.231936	0.10				
850	0.236884	0.10				
900	0.237011	0.10				
950	0.234186	0.10				
1000	0.228236	0.10				
1100	0.210707	0.30				
1200	0.190255	0.30				
1300	0.168811	0.30				
1400	0.147779	0.35				
1500	0.129501	0.40				
1600	0.112764	0.40				

Table A.2.3 Spectral irradiances measured from 3 runs for lamp FEL6.

Wavelength nm	Cumulative lamp burn time at end of test: 2.0 h		4.0 h		6.0 h	
	Spectral Irradiance W m^{-2} nm^{-1}	Transfer Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Transfer Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Transfer Std Dev. %
Spectral bandwidth: 2 nm						
250	0.00027	2.90	0.000271	4.17	0.000271	3.16
260	0.000461	0.87	0.000464	1.20	0.000467	0.93
270	0.000753	0.33	0.000755	0.43	0.000759	0.35
280	0.001128	0.17	0.001124	0.22	0.001137	0.17
290	0.001729	0.10	0.001729	0.12	0.001744	0.11
300	0.002481	0.07	0.002476	0.10	0.002507	0.08
310	0.003472	0.05	0.003467	0.06	0.003509	0.06
320	0.004678	0.04	0.004666	0.05	0.004712	0.04
330	0.006176	0.03	0.006171	0.03	0.006222	0.04
340	0.007997	0.02	0.008004	0.03	0.008057	0.03
350	0.010164	0.02	0.010149	0.03	0.01022	0.02
360	0.012695	0.02	0.012644	0.02	0.012745	0.02
370	0.015565	0.02	0.015525	0.02	0.015641	0.02
380	0.018828	0.02	0.0188	0.02	0.018926	0.02
390	0.02243	0.01	0.022458	0.02	0.022584	0.01
400	0.026474	0.01	0.026466	0.02	0.026588	0.02
450	0.051721	0.01	0.051672	0.01	0.05183	0.01
500	0.08338	0.01	0.0834	0.01	0.083408	0.01
550	0.117333	0.01	0.117333	0.01	0.117333	0.01
600	0.149968	0.01	0.149871	0.01	0.149929	0.01
650	0.178628	0.01	0.178509	0.01	0.17846	0.01
700	0.201657	0.01	0.201568	0.02	0.201534	0.01
Spectral bandwidth: 4 nm						
750	0.218506	0.01	0.217954	0.01	0.217856	0.01
800	0.229287	0.01	0.228868	0.01	0.228378	0.01
850	0.234492	0.01		0.01	0.23374	0.01
900	0.235572	0.01		0.01	0.234462	0.01
950	0.23284	0.01		0.01	0.231643	0.01
1000	0.226988	0.01	0.22622	0.01	0.226063	0.01
1100	0.209461	0.02	0.209127	0.02	0.2093	0.02
1200	0.189027	0.01	0.18912	0.01		
1300	0.168035	0.01	0.167751	0.01		
1400	0.147273	0.01	0.14687	0.01		
1500	0.128654	0.01	0.128757	0.01		
1600	0.111943	0.01	0.112176	0.01		

A.2.2 SPRING results

All measurements were done in the period 29 November – 1 December 2003

The cumulative lamp burn times are from the start of the round 1 measurements at NMIA.

Table A.2.4 Spectral irradiances measured from 4 runs for lamp FEL1. Ambient temperature 23°C Standard deviations are for single transfers only

Wavelength nm	Cumulative lamp burn time at end of test 6.8 h		7.7 h		8.5 h		9.3 h	
	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %
Spectral bandwidth: 2.5 nm								
250	2.799E-04	0.34	2.783E-04	0.46	2.766E-04	0.32	2.743E-04	0.17
260	4.804E-04	0.12	4.747E-04	0.37	4.741E-04	0.19	4.728E-04	0.19
270	7.786E-04	0.15	7.727E-04	0.06	7.678E-04	0.08	7.707E-04	0.18
280	1.195E-03	0.05	1.183E-03	0.09	1.181E-03	0.11	1.185E-03	0.12
290	1.774E-03	0.12	1.761E-03	0.08	1.755E-03	0.03	1.762E-03	0.06
300	2.526E-03	0.12	2.510E-03	0.04	2.505E-03	0.08	2.516E-03	0.07
310	3.548E-03	0.04	3.508E-03	0.04	3.525E-03	0.01	3.529E-03	0.04
320	4.742E-03	0.08	4.693E-03	0.06	4.715E-03	0.02	4.714E-03	0.08
330	6.251E-03	0.12	6.182E-03	0.05	6.212E-03	0.05	6.223E-03	0.09
340	8.072E-03	0.04	7.987E-03	0.06	8.046E-03	0.05	8.048E-03	0.04
350	1.024E-02	0.03	1.013E-02	0.06	1.019E-02	0.03	1.019E-02	0.03
360	1.272E-02	0.04	1.258E-02	0.08	1.267E-02	0.02	1.268E-02	0.03
370	1.559E-02	0.03	1.543E-02	0.04	1.552E-02	0.02	1.553E-02	0.06
380	1.884E-02	0.04	1.864E-02	0.02	1.874E-02	0.01	1.874E-02	0.02
390	2.242E-02	0.03	2.218E-02	0.02	2.233E-02	0.05	2.235E-02	0.02
400	2.641E-02	0.02	2.613E-02	0.02	2.628E-02	0.02	2.632E-02	0.03
450	5.105E-02	0.01	5.070E-02	0.03	5.082E-02	0.02	5.093E-02	0.02
500	8.194E-02	0.00	8.130E-02	0.05	8.160E-02	0.03	8.185E-02	0.01
550	1.150E-01	0.03	1.140E-01	0.04	1.146E-01	0.01	1.150E-01	0.04
600	1.464E-01	0.01	1.448E-01	0.02	1.460E-01	0.02	1.465E-01	0.01
650	1.738E-01	0.02	1.721E-01	0.04	1.735E-01	0.03	1.741E-01	0.01
700	1.956E-01	0.02	1.933E-01	0.04	1.951E-01	0.03	1.959E-01	0.03
750	2.115E-01	0.03	2.090E-01	0.04	2.112E-01	0.04	2.120E-01	0.02
800	2.210E-01	0.05	2.184E-01	0.04	2.210E-01	0.06	2.219E-01	0.03
850	2.252E-01	0.05	2.232E-01	0.16	2.257E-01	0.21	2.263E-01	0.11
900	2.256E-01	0.03	2.260E-01	0.05	2.266E-01	0.08	2.266E-01	0.04
950	2.223E-01	0.03	2.229E-01	0.04	2.234E-01	0.03	2.235E-01	0.04
1000	2.170E-01	0.04	2.171E-01	0.02	2.179E-01	0.01	2.180E-01	0.01
Spectral bandwidth: 5.0 nm								
1100	2.015E-01	0.03	2.013E-01	0.03	2.014E-01	0.03	2.019E-01	0.02
1200	1.815E-01	0.03	1.814E-01	0.01	1.815E-01	0.02	1.818E-01	0.02
1300	1.607E-01	0.02	1.607E-01	0.01	1.609E-01	0.03	1.611E-01	0.02
1400	1.389E-01	0.04	1.411E-01	0.06	1.410E-01	0.03	1.412E-01	0.04
1500	1.223E-01	0.01	1.222E-01	0.01	1.226E-01	0.03	1.228E-01	0.04
1600	1.073E-01	0.01	1.071E-01	0.04	1.075E-01	0.04	1.077E-01	0.03

Table A.2.5 Spectral irradiances measured from 4 runs for lamp FEL5. Ambient temperature 23ºC Standard deviations are for transfers only

Wavelength nm	Cumulative lamp burn time at end of test							
	9.8 h		10.7 h		11.5 h		12.3 h	
	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %
Spectral bandwidth: 2.5 nm								
250	2.888E-04	0.27	2.848E-04	0.15	2.814E-04	0.07	2.806E-04	0.25
260	4.933E-04	0.13	4.899E-04	0.11	4.814E-04	0.25	4.843E-04	0.15
270	8.021E-04	0.17	7.958E-04	0.18	7.821E-04	0.09	7.836E-04	0.21
280	1.203E-03	0.14	1.192E-03	0.02	1.173E-03	0.08	1.177E-03	0.11
290	1.821E-03	0.02	1.812E-03	0.01	1.788E-03	0.10	1.794E-03	0.04
300	2.604E-03	0.03	2.589E-03	0.07	2.561E-03	0.06	2.572E-03	0.07
310	3.648E-03	0.12	3.608E-03	0.03	3.590E-03	0.07	3.596E-03	0.09
320	4.892E-03	0.05	4.836E-03	0.06	4.810E-03	0.08	4.831E-03	0.06
330	6.468E-03	0.07	6.386E-03	0.06	6.361E-03	0.01	6.385E-03	0.03
340	8.364E-03	0.08	8.267E-03	0.05	8.225E-03	0.01	8.266E-03	0.03
350	1.062E-02	0.04	1.050E-02	0.02	1.043E-02	0.03	1.049E-02	0.02
360	1.320E-02	0.04	1.305E-02	0.01	1.299E-02	0.03	1.305E-02	0.02
370	1.617E-02	0.05	1.603E-02	0.03	1.594E-02	0.03	1.599E-02	0.04
380	1.956E-02	0.02	1.934E-02	0.03	1.927E-02	0.03	1.931E-02	0.00
390	2.329E-02	0.03	2.308E-02	0.02	2.298E-02	0.01	2.304E-02	0.03
400	2.742E-02	0.02	2.718E-02	0.00	2.708E-02	0.03	2.716E-02	0.03
450	5.330E-02	0.02	5.288E-02	0.04	5.274E-02	0.01	5.272E-02	0.00
500	8.551E-02	0.03	8.493E-02	0.02	8.486E-02	0.04	8.481E-02	0.02
550	1.200E-01	0.03	1.192E-01	0.01	1.193E-01	0.01	1.194E-01	0.01
600	1.526E-01	0.06	1.517E-01	0.02	1.518E-01	0.01	1.523E-01	0.02
650	1.813E-01	0.01	1.805E-01	0.03	1.809E-01	0.02	1.810E-01	0.02
700	2.039E-01	0.07	2.029E-01	0.05	2.034E-01	0.00	2.039E-01	0.00
750	2.206E-01	0.01	2.193E-01	0.04	2.200E-01	0.02	2.209E-01	0.03
800	2.308E-01	0.01	2.301E-01	0.05	2.301E-01	0.02	2.315E-01	0.03
850	2.359E-01	0.05	2.352E-01	0.10	2.348E-01	0.05	2.360E-01	0.10
900	2.382E-01	0.03	2.387E-01	0.04	2.382E-01	0.06	2.382E-01	0.02
950	2.343E-01	0.03	2.347E-01	0.01	2.346E-01	0.03	2.351E-01	0.01
1000	2.284E-01	0.03	2.289E-01	0.03	2.285E-01	0.01	2.292E-01	0.02
Spectral bandwidth: 5.0 nm								
1100	2.120E-01	0.00	2.120E-01	0.02	2.121E-01	0.01	2.119E-01	0.03
1200	1.911E-01	0.02	1.910E-01	0.01	1.910E-01	0.04	1.910E-01	0.01
1300	1.694E-01	0.03	1.693E-01	0.02	1.693E-01	0.01	1.693E-01	0.04
1400	1.463E-01	0.02	1.485E-01	0.02	1.483E-01	0.01	1.480E-01	0.02
1500	1.288E-01	0.03	1.289E-01	0.01	1.289E-01	0.02	1.292E-01	0.01
1600	1.130E-01	0.01	1.128E-01	0.02	1.130E-01	0.01	1.132E-01	0.01

Table A.2.6 Spectral irradiances measured from 4 runs for lamp FEL6. Ambient temperature 23ºC Standard deviations are for transfers only

Wavelength nm	Cumulative lamp burn time at end of test							
	6.8 h		7.7 h		8.5 h		9.3 h	
	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Std Dev. %
Spectral bandwidth: 2.5 nm								
250	2.703E-04	0.31	2.672E-04	0.40	2.653E-04	0.46	2.613E-04	0.27
260	4.635E-04	0.08	4.593E-04	0.08	4.572E-04	0.24	4.520E-04	0.21
270	7.559E-04	0.17	7.484E-04	0.12	7.457E-04	0.04	7.355E-04	0.11
280	1.130E-03	0.11	1.123E-03	0.16	1.119E-03	0.06	1.108E-03	0.09
290	1.727E-03	0.03	1.715E-03	0.03	1.708E-03	0.10	1.694E-03	0.05
300	2.471E-03	0.10	2.457E-03	0.07	2.456E-03	0.06	2.436E-03	0.11
310	3.468E-03	0.11	3.456E-03	0.09	3.425E-03	0.06	3.396E-03	0.09
320	4.667E-03	0.02	4.643E-03	0.08	4.613E-03	0.03	4.584E-03	0.04
330	6.168E-03	0.07	6.142E-03	0.01	6.103E-03	0.06	6.065E-03	0.04
340	7.999E-03	0.03	7.958E-03	0.04	7.903E-03	0.04	7.844E-03	0.09
350	1.016E-02	0.04	1.011E-02	0.04	1.005E-02	0.03	9.980E-03	0.04
360	1.265E-02	0.04	1.260E-02	0.02	1.253E-02	0.02	1.242E-02	0.05
370	1.554E-02	0.07	1.548E-02	0.03	1.538E-02	0.03	1.526E-02	0.03
380	1.878E-02	0.02	1.871E-02	0.03	1.862E-02	0.04	1.848E-02	0.01
390	2.242E-02	0.03	2.233E-02	0.01	2.221E-02	0.03	2.204E-02	0.04
400	2.641E-02	0.02	2.634E-02	0.04	2.620E-02	0.02	2.600E-02	0.01
450	5.134E-02	0.01	5.125E-02	0.05	5.129E-02	0.02	5.094E-02	0.02
500	8.292E-02	0.04	8.273E-02	0.03	8.271E-02	0.03	8.226E-02	0.02
550	1.171E-01	0.02	1.168E-01	0.00	1.166E-01	0.03	1.159E-01	0.04
600	1.495E-01	0.01	1.492E-01	0.04	1.489E-01	0.03	1.480E-01	0.02
650	1.784E-01	0.04	1.779E-01	0.02	1.774E-01	0.04	1.763E-01	0.02
700	2.009E-01	0.04	2.007E-01	0.05	2.000E-01	0.05	1.987E-01	0.03
750	2.182E-01	0.01	2.174E-01	0.01	2.167E-01	0.01	2.155E-01	0.05
800	2.286E-01	0.08	2.275E-01	0.10	2.270E-01	0.01	2.261E-01	0.02
850	2.328E-01	0.16	2.331E-01	0.10	2.320E-01	0.05	2.314E-01	0.05
900	2.343E-01	0.03	2.346E-01	0.04	2.358E-01	0.03	2.350E-01	0.03
950	2.309E-01	0.02	2.314E-01	0.03	2.326E-01	0.03	2.315E-01	0.01
1000	2.252E-01	0.07	2.258E-01	0.01	2.270E-01	0.01	2.257E-01	0.01
Spectral bandwidth: 5.0 nm								
1100	2.097E-01	0.01	2.095E-01	0.02	2.103E-01	0.02	2.095E-01	0.01
1200	1.892E-01	0.03	1.891E-01	0.01	1.897E-01	0.01	1.888E-01	0.01
1300	1.679E-01	0.05	1.677E-01	0.02	1.683E-01	0.03	1.676E-01	0.01
1400	1.450E-01	0.01	1.474E-01	0.02	1.474E-01	0.01	1.465E-01	0.03
1500	1.281E-01	0.03	1.281E-01	0.01	1.283E-01	0.03	1.276E-01	0.06
1600	1.123E-01	0.02	1.123E-01	0.01	1.124E-01	0.02	1.120E-01	0.02

A.2.3 NMIA round 2 results

New measurements of relative spectral irradiances of these lamps for round 2 were done in the period 10 – 13 August 2004. Measurements of lamp illuminances used to normalise these relative units to SI spectral irradiance units were done in the period 15 – 17 December 2003. Minimum number of measurements made at each wavelength from which the transfer standard deviation is calculated = 50. The cumulative lamp burn times are from the start of the round 1 measurements at NMIA.

Table A.2.7 Spectral irradiances measured from 3 runs for lamp FEL1. Ambient temperature 21ºC

Wavelength nm	Cumulative lamp burn time at end of test					
	12.8 h		14.8 h		17.5 h	
	Spectral Irradiance W m^{-2} nm^{-1}	Transfer Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Transfer Std Dev. %	Spectral Irradiance W m^{-2} nm^{-1}	Transfer Std Dev. %
Spectral bandwidth: 2 nm						
250	0.000278	5.10	0.000282	5.05	0.000287	5.13
260	0.000476	1.51	0.00048	1.49	0.000483	1.52
270	0.000775	0.55	0.000778	0.54	0.000784	0.55
280	0.001188	0.26	0.001186	0.25	0.001202	0.25
290	0.001775	0.14	0.001773	0.14	0.001785	0.14
300	0.00253	0.09	0.002529	0.09	0.002548	0.09
310	0.003552	0.06	0.00355	0.06	0.00357	0.06
320	0.004748	0.04	0.004736	0.04	0.004763	0.04
330	0.006252	0.04	0.006247	0.03	0.006284	0.04
340	0.008086	0.03	0.008051	0.02	0.008117	0.03
350	0.010234	0.03	0.010217	0.02	0.010268	0.02
360	0.012736	0.02	0.012734	0.02	0.012774	0.02
370	0.01561	0.02	0.015596	0.02	0.015655	0.02
380	0.018862	0.01	0.018825	0.02	0.018913	0.02
390	0.022434	0.01	0.022404	0.01	0.022519	0.02
400	0.026406	0.02	0.02637	0.01	0.02648	0.01
450	0.0512	0.01	0.051165	0.01	0.051278	0.01
500	0.082029	0.01	0.082029	0.01	0.082077	0.01
550	0.115032	0.01	0.115027	0.01	0.115034	0.01
600	0.146354	0.01	0.14644	0.01	0.146436	0.01
650	0.173886	0.01	0.173876	0.01	0.174063	0.01
700	0.195573	0.01	0.195957	0.01	0.195527	0.01
Spectral bandwidth: 4 nm						
750	0.210984	0.01	0.211735	0.01	0.211147	0.01
800	0.220806	0.01	0.221688	0.01	0.221261	0.01
850	0.225234	0.01	0.226437	0.01	0.225531	0.01
900	0.225866	0.01	0.227105	0.01	0.225598	0.01
950	0.222879	0.01	0.224161	0.01	0.222601	0.01
1000	0.217208	0.01	0.218623	0.01	0.216868	0.01
Spectral bandwidth: 8 nm						
1100	0.201074	0.02	0.201567	0.01	0.200779	0.02
1200	0.181383	0.02	0.181826	0.01	0.180892	0.01
1300	0.16086	0.02	0.161676	0.01	0.160622	0.01
1400	0.140887	0.02	0.14184	0.01	0.140894	0.01
1500	0.122915	0.02	0.123665	0.01	0.122962	0.01
1600	0.107275	0.02	0.107594	0.01	0.107086	0.01

Table A.2.8 Spectral irradiances measured from 3 runs for lamp FEL5. Ambient temperature 21ºC

Wavelength nm	Cumulative lamp burn time at end of test					
	16.1 h		18.0 h		20.0 h	
	Spectral Irradiance W m⁻² nm⁻¹	Transfer Std Dev. %	Spectral Irradiance W m⁻² nm⁻¹	Transfer Std Dev. %	Spectral Irradiance W m⁻² nm⁻¹	Transfer Std Dev. %
Spectral bandwidth: 2 nm						
250	0.000287	5.13	0.00029	4.88	0.000292	5.08
260	0.000495	1.52	0.000488	1.45	0.000488	1.49
270	0.000804	0.56	0.000791	0.53	0.000791	0.54
280	0.001205	0.27	0.001186	0.25	0.001186	0.26
290	0.001828	0.14	0.001814	0.13	0.001813	0.14
300	0.002613	0.09	0.002593	0.08	0.00259	0.08
310	0.003653	0.06	0.003636	0.06	0.003632	0.06
320	0.004908	0.05	0.004878	0.04	0.004868	0.04
330	0.00647	0.04	0.006439	0.03	0.006432	0.04
340	0.008373	0.03	0.008336	0.03	0.008309	0.03
350	0.010598	0.03	0.010563	0.02	0.010552	0.03
360	0.013202	0.02	0.01316	0.02	0.013153	0.02
370	0.016187	0.02	0.016137	0.02	0.016127	0.02
380	0.019561	0.02	0.019523	0.02	0.019471	0.01
390	0.023333	0.01	0.023242	0.01	0.023194	0.01
400	0.02747	0.01	0.027349	0.01	0.02735	0.01
450	0.053282	0.01	0.053225	0.01	0.053223	0.01
500	0.085532	0.01	0.085516	0.01	0.085504	0.01
550	0.120174	0.01	0.120122	0.01	0.120145	0.01
600	0.153125	0.01	0.153077	0.01	0.153117	0.01
650	0.182079	0.01	0.182003	0.01	0.181917	0.01
700	0.204913	0.01	0.204746	0.01	0.205236	0.01
Spectral bandwidth: 4 nm						
750	0.221449	0.02	0.221196	0.01	0.222106	0.01
800	0.232347	0.02	0.231807	0.01	0.23273	0.01
850	0.236924	0.02	0.236565	0.01	0.237756	0.01
900	0.236992	0.02	0.237106	0.01	0.238448	0.01
950	0.234031	0.02	0.234133	0.01	0.235547	0.01
1000	0.228194	0.02	0.228292	0.01	0.229776	0.01
Spectral bandwidth: 8 nm						
1100	0.210017	0.02	0.211389	0.01	0.213209	0.02
1200	0.19032	0.02	0.19083	0.01	0.192142	0.02
1300	0.168682	0.02	0.169242	0.01	0.170582	0.02
1400	0.148154	0.02	0.148371	0.01	0.149688	0.02
1500	0.12928	0.02	0.129549	0.01	0.130571	0.02
1600	0.11256	0.02	0.113179	0.01	0.113804	0.02

Table A.2.9 Spectral irradiances measured from 3 runs for lamp FEL6. Ambient temperature 21ºC

Wavelength nm	Cumulative lamp burn time at end of test 17.5 h		20.0 h		22.5 h	
	Spectral Irradiance W m⁻² nm⁻¹	Transfer Std Dev. %	Spectral Irradiance W m⁻² nm⁻¹	Transfer Std Dev. %	Spectral Irradiance W m⁻² nm⁻¹	Transfer Std Dev. %
Spectral bandwidth: 2 nm						
250	0.000268	4.90	0.000268	4.83	0.000271	4.88
260	0.000457	1.45	0.000457	1.43	0.000462	1.44
270	0.000746	0.53	0.000746	0.52	0.000755	0.52
280	0.001119	0.26	0.001118	0.24	0.001135	0.24
290	0.001717	0.13	0.001715	0.13	0.001723	0.13
300	0.002459	0.09	0.002457	0.09	0.002476	0.09
310	0.003449	0.06	0.003447	0.06	0.003461	0.06
320	0.004635	0.04	0.004635	0.05	0.004657	0.05
330	0.006128	0.03	0.00613	0.03	0.006157	0.03
340	0.007926	0.03	0.007943	0.03	0.007974	0.03
350	0.010084	0.02	0.010081	0.02	0.010118	0.02
360	0.012592	0.02	0.012584	0.02	0.012613	0.02
370	0.015445	0.02	0.015447	0.02	0.015494	0.02
380	0.018677	0.02	0.018709	0.01	0.018754	0.02
390	0.022272	0.01	0.02231	0.01	0.022388	0.01
400	0.026302	0.01	0.026299	0.01	0.026382	0.01
450	0.051445	0.01	0.051409	0.01	0.05141	0.01
500	0.082876	0.01	0.082895	0.01	0.082894	0.01
550	0.116848	0.01	0.116787	0.01	0.116825	0.01
600	0.149277	0.01	0.149163	0.01	0.149261	0.01
650	0.177724	0.01	0.177747	0.01	0.177774	0.01
700	0.200758	0.01	0.200462	0.01	0.200504	0.01
Spectral bandwidth: 4 nm						
750	0.217576	0.01	0.216984	0.01	0.216807	0.01
800	0.228383	0.01	0.22785	0.01	0.227511	0.01
850	0.233589	0.01	0.232724	0.01	0.232443	0.01
900	0.234536	0.01	0.233089	0.01	0.233256	0.01
950	0.231918	0.01	0.230437	0.01	0.230507	0.01
1000	0.226412	0.01	0.224779	0.01	0.22486	0.01
Spectral bandwidth: 8 nm						
1100	0.209892	0.02	0.208482	0.01	0.207401	0.02
1200	0.189702	0.01	0.188143	0.01	0.187551	0.01
1300	0.168265	0.02	0.167108	0.01	0.166863	0.01
1400	0.147552	0.02	0.147084	0.01	0.146443	0.01
1500	0.128946	0.01	0.128331	0.01	0.127933	0.01
1600	0.112602	0.02	0.111788	0.01	0.11137	0.01

A.3 Description of the measurement facility and traceability

A.3.1 NMIA laboratory

The spectral irradiance units are based on two inputs:

- the NML2003 scale of relative spectral irradiance (1), and
- the NML1997 unit of illuminance (2).

The measured values of relative spectral irradiance normalised at 550 nm are used together with illuminance measurements from the lamps at the required distance to normalise the relative values to SI spectral irradiance units. The independently established NML 1997 illuminance unit is used for this.

To establish the NML2003 scale of relative spectral irradiance, filter radiometers with spectral bandwidths of about 50 nm and peak wavelengths near 340, 450, 550, 700, 940, 1300 and 1540 nm have been built and fitted four at a time into an integrating sphere and calibrated in the sphere for spectral responsivity using the NML1998 scale of spectral responsivity (3). Measurements of signal ratios from pairs of radiometers were made for flux entering the sphere from each of several types of tungsten halogen reference lamps operated at between 3000 and 3200 K distribution temperature.

The lamps were then compared spectrally with a high-temperature graphite blackbody operated at a temperature of between 2850 and 2950K. A mirror optical system was constructed to allow comparison of irradiance from the whole lamp and from a part of the bottom of the cavity wall with a diameter of about 2 mm in such a way that the spectral reflection function of the system was common to both sources and therefore did not have to be measured. More details of the blackbody and optical systems used for this will be provided in reference 1.

For each lamp the measured relative spectral power ratios $\rho(\lambda)$ are used with the signal ratios S_1 / S_2 from each pair of filter radiometers to find the blackbody temperature T that solves the following equation (2):

$$E(\lambda) = L(\lambda,T)\,\rho(\lambda); \qquad (1)$$

$$S_1 / S_2 = \int E(\lambda)R_1(\lambda)d\lambda \,/\, \int E(\lambda)R_2(\lambda)d\lambda$$
$$= \int L(\lambda,T)\,\rho(\lambda)R_1(\lambda)d\lambda \,/\, \int L(\lambda,T)\,\rho(\lambda)R_2(\lambda)d\lambda \qquad (2)$$

where $E(\lambda)$ is the lamp relative spectral irradiance, $L(\lambda,T)$ is the blackbody relative spectral radiance at temperature T, and $R_1(\lambda)$ and $R_2(\lambda)$ are the radiometer spectral responses. All distributions are normalised to unity at the same wavelength. The lamp spectral power distribution is then given by equation (1).

The system used to transfer the relative spectral irradiances from the NMIA reference standards to the transfer lamps used for this comparison consists of a **McPherson model 285 grating monochromator fitted with a model 608M1 quartz prism pre-disperser**. The monochromator was used with **either single or double gratings** for different wavelength ranges, as indicated in Table A.3.1. For infra-red wavelength measurements an additional RG780 filter or a silicon filter was used as an order-sorter and reduce the level of stray-light.

Table A.3.1 Monochromators and detectors used for comparing spectral irradiance lamps

Wavelength range (nm)	Mono-chromator	Blaze wave-length (nm)	Spectral bandwidth (nm)	Detector	Amplifier, gain
240 – 900	Double	300	2	Hamamatsu R562 PMT #SA4965	AD515KH op amp 1 Mohm
400 – 750	Double	500	2	Hamamatsu Si S1337-1010BQ	AD515KH op amp 1 Gohm
800 – 1700	Single (round 1) Double (round 2)	1000 1000	8 4	Telcom Devices InGaAs # TD1	AD515KH op amp 100 Mohm

The configuration of the lamps and input optics is shown in Figure A.3.1.

The two lamps, housed as described later in this section, irradiate in turn at normal incidence a plane 50x50 mm $BaSO_4$ plate (Karl Lüers). Lamp – plate distances are from 500 to 600 mm (for measurement of relative spectral irradiances only). The plate is rotated through 90° to face either lamp and flux reflected by the plate on an axis approx. 45° from the normal is collected by a small concave spherical mirror M1 and directed over the plate to a second spherical mirror M2 which images the first mirror onto the monochromator entrance slit via a plane mirror, M3. The effective target area of the plate viewed by the monochromator is oval, approx 40x30 mm. The system is symmetric about the vertical plane containing the monochromator entrance beam axis. Lamp positions are swapped to check and correct for any small level of spectral bias between the two positions.

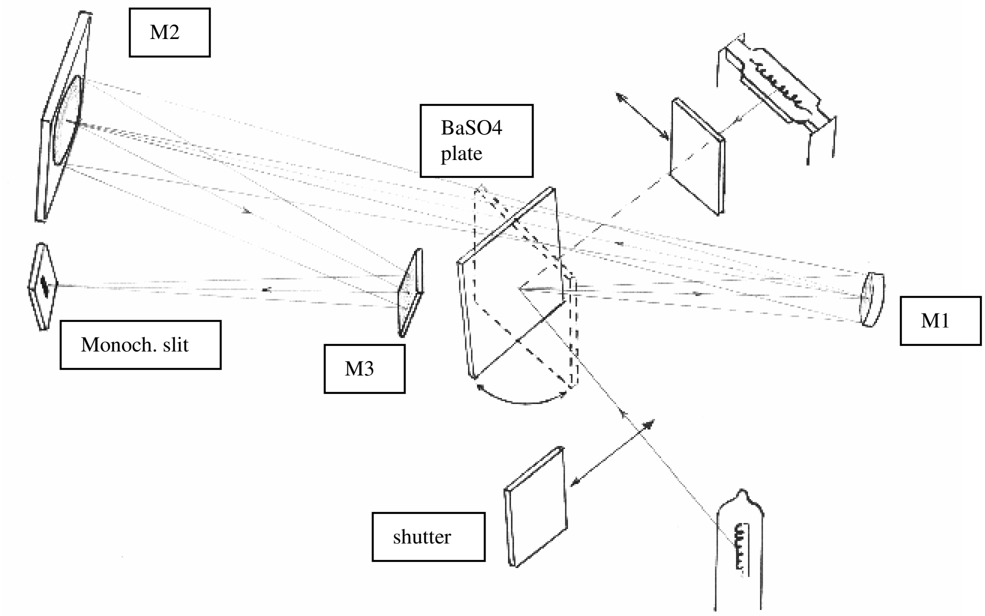

Figure A.3.1 Spectral irradiance target optics used at NMIA

Three types of detectors and circuits were used for the lamp comparisons. Details of these are given in Table A.3.1.

The reference lamps that were used are all of the tungsten halogen type. The lamps that were calibrated from the blackbody as described above and then used to calibrate the transfer lamps for this bilateral comparison were:

- one Ushio Electric 100 V 500 W (as used in the 1975 CCPR key comparison),
- one GE FEL 120 V 1000 W (transfer lamp in 1990)
- three Sylvania FEL 120 V 1000 W.

These lamps were operated at distribution temperatures between 3100 and 3200 K. They therefore had similar distribution temperatures and power levels to those of these transfer lamps. Therefore, the low levels of uncertainty assessed for stray-light and wavelength effects resulted from the common influences these have on both reference and test lamps.

For the illuminance measurements, they were used to normalise the relative spectral irradiances to SI units of spectral irradiance at the required measurement distance, a set of four lamp standards of illuminance was used to calibrate a photometer that was then used to measure the transfer lamp illuminance values. These illuminance standards were

- Philips type 6369 24 V 250 W,

which were operated at a distribution temperature of 2856K.

This whole procedure was done on three occasions. After correcting the measured illuminances for differences between the spectra of the illuminance standards (at Illuminant A) and the spectral irradiance lamps (at distribution temperature about 3000K) and the mismatch of the photometer spectral response with V(λ), one illuminance value was combined with one of the measured sets of relative spectral irradiances to obtain three independent sets of absolute spectral irradiances. The degree of correlation of these is assessed as <10%.

Measurements at NMIA were reported to be done at an ambient temperature of 21º ± 0.5ºC and relative humidity of 50 ± 10%. The transfer lamps were measured by comparing them with similar FEL-type lamps at the same distances from the spectroradiometer. These conditions are therefore considered to be suitable for this comparison and the differences are not significant.

The spectral bandwidths used at NMIA varied from 2 nm at UV and visible wavelengths to 4 nm or 8 nm at IR wavelengths. As the transfer lamps were being compared with similar lamps operated at similar distribution temperatures (within ~ 150K), shifts in effective wavelengths are similar for both lamps and these bandwidths are considered to be appropriate for this comparison and differences are not significant.

At NMIA, measurements were done with the lamps mounted in a cylinder of diameter 310 mm, height 420 mm, open at the top and with a 50 mm gap between the bottom of the cylinder and the top of the table to allow natural circulation of room air. The cylinder is painted matt black and has a 90 mm-diameter viewing aperture opposite the lamp and a 200 mm-diameter aperture behind the lamp that is covered by a conical gloss-black light-trap. The measurement system could not see any of the cylinder wall. The reference lamps were similarly housed.

A.3.2 SPRING laboratory

A.3.2.1 Makers and types of spectroradiometer:

The spectroradiometer used for the calibration is developed internally at National Metrology centre, SPRING Singapore. It uses a double-grating monochromator (model DK242 made by CVI Laser) which has a focal length of 240 mm. An integrating sphere, 50mm in diameter, is used to reduce the polarisation effect of the source and provide a uniform input for the monochromator. A ϕ25mm end-on photomultiplier (PMT) (Hamamatsu R374, 11 stages) is used to cover the wavelength range of 250 nm to 850 nm, and an electrically cooled InGaAs detector (Hamamatsu G6126) is used to cover the wavelength range of 850 nm to 1600 nm. The temperature around the monochromator and the detector is PID controlled to within +/- 0.1 °C to maintain the wavelength accuracy and stable responsivity of the detectors. This arrangement provides a signal-to-noise ratio of better than 500 over the wavelength range of 300nm to 1600 nm and a signal-to-noise-ratio of 200 over the wavelength range of 250nm to 300nm.

A.3.2.2 Laboratory reference standards used:

- Four number of NIST issued FEL spectral irradiance standards.
- Standard resistor traceable to SPRING's resistance scale.
- Digital volt meter traceable to SPRING's DC voltage scale.
- 500 mm distance gauge traceable to SPRING's length scale.

A.3.2.3 The measuring set-up is illustrated in the following diagram:

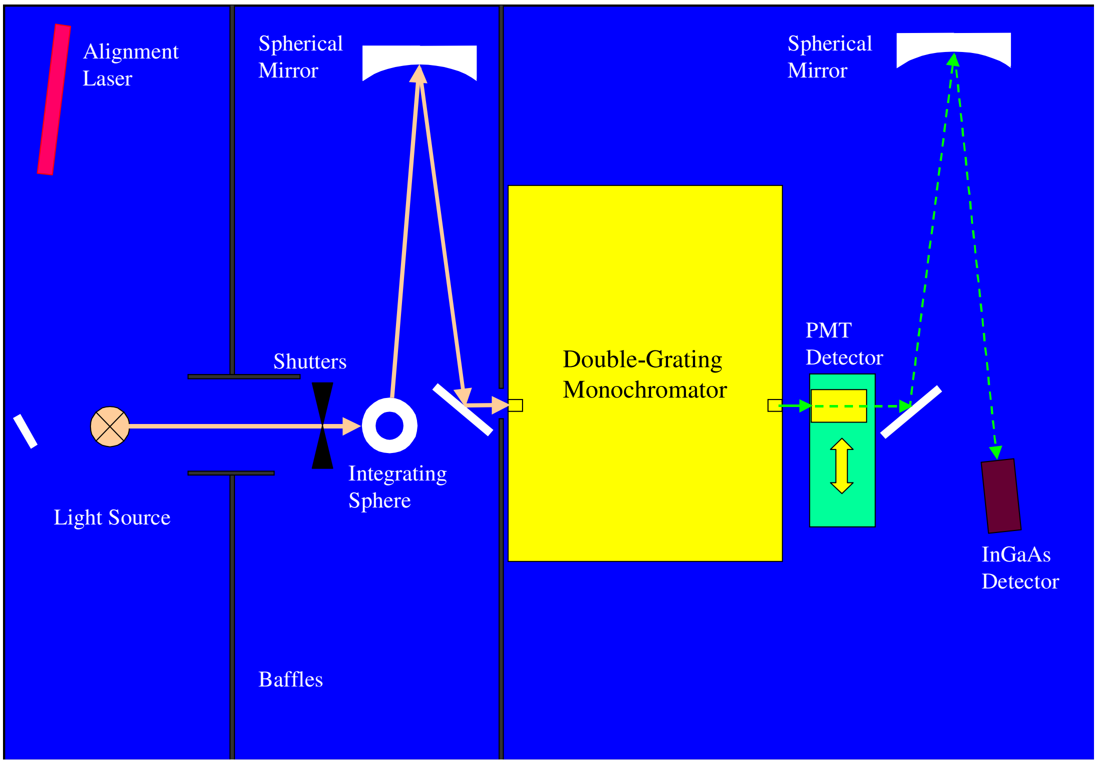

Figure A.3.2 SPRING's Spectral Irradiance Calibration Facility

One cycle of calibration is carried out by measuring a standard lamp first, then followed by the measurements of the 3 test lamps and finally the repeat measurement of the same standard lamp to check the stability of the system responsivity.

A.3.2.4 Establishment of traceability route of the spectral irradiance scale including date of last realisation and breakdown of uncertainty:

The SPRING spectral irradiance scale is maintained on four number of NIST issued FEL spectral irradiance standards with the latest standard lamp received in year 2002 that has a total burn time of less than 10 hours to date. The uncertainties of the NIST issued lamps range from 1.82% at 250nm, 0.91% at 654.6nm and 1.42% at 1600nm. More details can be found in the NIST document : NBS Special Publication 250-20 (1987), Spectral Irradiance Calibrations. The uncertainties involved using this facility together with the NIST standards are detailed in a separated Excel file.

A.3.2.5 Description of calibration laboratory conditions: (eg. Temperature, relative humidity etc.)

The temperature of the laboratory is maintained at 23°C +/- 2°C and the relative humidity is maintained at 60% +/- 10%.

The transfer lamps were measured in both laboratories by comparing them with similar FEL-type lamps at the same distances from the spectroradiometers. These conditions are therefore considered to be suitable for this comparison and the differences are not significant.

At the SPRING laboratory the spectral bandwidths were 2.5 nm at wavelengths 250 – 1000 nm and 5 nm from 1100 to 1600 nm. As the transfer lamps were being compared with similar lamps operated at similar distribution temperatures (within ~ 150K), shifts in effective wavelengths are similar for both lamps and these bandwidths are considered to be appropriate for this comparison and differences are not significant.

At the SPRING laboratory each lamp was operated inside a blackened housing together with input optics of the spectroradiometer. A black velveteen curtain was placed behind the lamp at a distance of about 700 mm to minimise any back scattering. Vents at the bottom, top and two sides of the enclosure were allowed for natural air convection. Baffles were placed between the lamp and the input optics to reduce any stray light. The reference lamps were similarly housed to the transfer lamps. The housings would have similar, though small, effects on both lamps and are also considered to result in no significant changes in spectral irradiances in either laboratory.

A.4 Record of lamp burn hours

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