

Report of the Spectral Irradiance Comparison
EURAMET.PR-K1.a.1
between MIKES (Finland) and NIMT (Thailand)

M. Ojanen¹, M. Shpak¹, P. Kärhä¹, R. Leecharoen², and E. Ikonen^{1,3}

¹*Helsinki University of Technology (TKK), Metrology Research Institute,
P. O. Box 3000, FI-02015 TKK, Finland*

²*National Institute of Metrology, Thailand (NIMT), Kluang Luang Patumthanee 12120, Thailand*

³*Centre for Metrology and Accreditation (MIKES), P. O. Box 9, FI-02151 Espoo, Finland*

Final Report

EURAMET.PR-K1.a.1

Abstract

A bilateral comparison of the spectral irradiance scales between MIKES (Finland) and NIMT (Thailand) was carried out at 22 wavelengths between 290 nm and 900 nm. MIKES acted as the pilot and link to the results of the key comparison CCPR-K1.a. The spectral irradiance values measured by NIMT generally agree with the key comparison reference value within the expanded uncertainty. Only exceptions are results at wavelengths 300 nm, 450 nm, and 500 nm, where the ratios between the degree of equivalence (DoE) and the expanded uncertainty of DoE ($k = 2$) are 1.0, 1.4, and 1.2, respectively.

1. Introduction

The Centre for Metrology and Accreditation (MIKES) and National Institute of Metrology, Thailand (NIMT) agreed in June 2007 to conduct a bilateral comparison on the spectral irradiance measurement of tungsten halogen lamps covering the spectral region from 290 nm to 900 nm. The aim of this bilateral comparison is to assess the equivalence of the spectral irradiance scales between the two institutes and link the results to the key comparison CCPR-K1.a, carried out in the years 2000-2003 [1]. The bilateral comparison was carried out according to a technical protocol approved in 2007 (http://kcdb.bipm.org/appendixB/appbresults/CCPR-K1.a/EURAMET.PR-K1.a.1_Technical_Protocol.pdf).

2. Form of the comparison

The pilot and link NMI i of the bilateral comparison is MIKES, while the linked NMI α is NIMT. The comparison was carried out through calibrations of a group of three transfer standard lamps prepared by MIKES. The lamps were labeled as BN-9101-245, -257, and -313. After measurements at MIKES, the lamps were hand-carried to NIMT for calibration. After the calibration at NIMT, these lamps were hand-carried back to MIKES for repeat calibration to monitor possible drifts. The measurements at MIKES were made in December 2006 and in February 2008. NIMT calibrated the transfer standard lamps in November 2007. The method used to link the results of the bilateral comparison to CCPR-K1.a and the primary spectral irradiance results are described in Appendices A and B, respectively.

3. Comparison artifacts

Three 1000-W tungsten halogen lamps of FEL-type were used as transfer standards in the spectral irradiance comparison between MIKES and NIMT. These lamps consist of a double coiled tungsten filament supported at the top and bottom of the filament and operated in a halogen filled quartz envelope. These lamps were operated with a constant current of nominal value 8.1000 A. The voltage across the lamp terminals was between 105 and 110 V for all three lamps. The resulting color temperature was approximately 3200 K. During the measurements, the current and voltage of the lamp were monitored. The lamp was supported by a post with six degrees of freedom for angular and spatial alignments. Each lamp had its own alignment jig to be fixed to the lamp base

when alignment is performed. The marked center of the alignment jig and the center of the detector/spectroradiometer entrance aperture defined the optical axis of the measurement with the help of a dual-beam alignment laser associated with the transfer standard lamps. The lamp calibration distance was measured with respect to the reference plane defined to be the front surface of the lamp base as shown in Fig. 1.

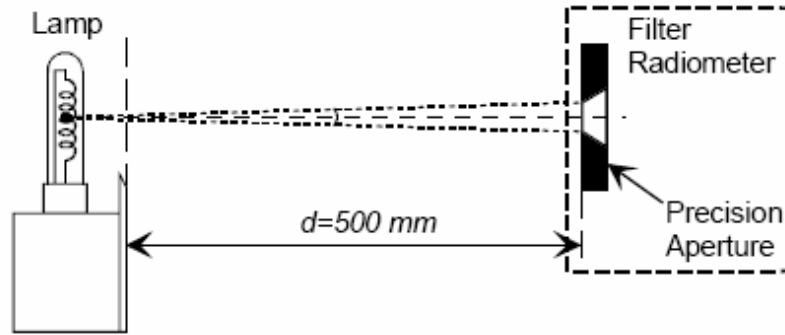


Figure 1. Outline of the MIKES transfer standard lamp and base. Distance to the entrance aperture of a filter radiometer or of a spectroradiometer is measured from the front surface of the lamp base.

4. Measurements at MIKES

The realization of the spectral irradiance scale at MIKES is described in Refs. [1-3] with detailed uncertainty budgets. The scale is based on absolutely characterized filter radiometers that consist of a trap detector made of three silicon photodiodes, interchangeable filters, and a precision aperture. The characterization of the filter radiometers is described in Refs. [2] and [3].

The calibration measurements at MIKES consist of recording the photocurrent signals of the filter radiometer with 15 filters of different peak transmission wavelengths. The lamp and the filter radiometer were aligned perpendicular to the optical axis using the dual-beam laser and reflections from the filter and the lamp alignment jig. The distance between the reference plane of the lamp and the aperture plane of the movable filter radiometer was set to 500.0 mm within 0.1 mm standard uncertainty by using an interferometrically calibrated magnetic displacement sensor on the measurement rail (see also Fig. 1). The standard uncertainty of the lamp current setting is 0.4 mA. One baffle with 10-cm diameter opening was placed in the middle between the lamp and the filter radiometer in order to reduce the effect of stray light.

5. Measurements at NIMT

The spectral irradiance scale at NIMT is traceable to the National Metrology Institute of Japan (NMIJ). Three NIMT primary standard lamps made by Ushio, Japan, (model JPD-100V-500WCS) were calibrated by NMIJ in constant voltage mode during the period from December 2006 to January 2007. These lamps have horizontal filaments and they are operated with a voltage of about 93 V. In the comparison measurements, the spectral irradiance of the MIKES transfer standard lamps was determined in terms of the spectral irradiance of the NIMT primary standard lamps by using the spectroradiometer setup outlined in Fig. 2.

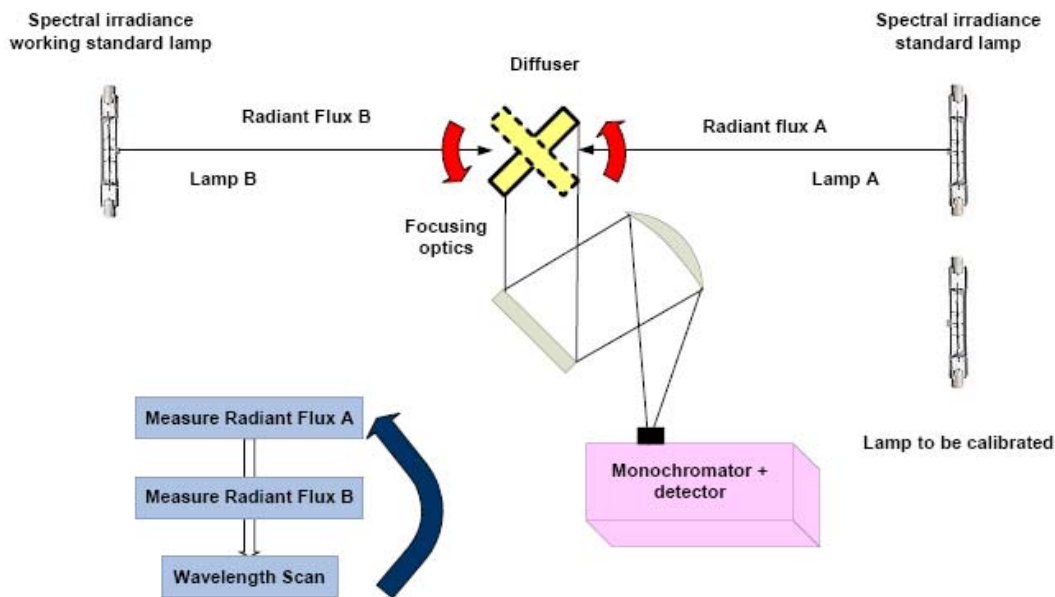


Figure 2. Measurement setup at NIMT [4].

The spectroradiometer is made by Bunkoh-Keiki, Japan. The main modules are a double subtractive monochromator and a detector housing which contains five different detectors. The photomultiplier tube R374 (Hamamatsu Photonics) and silicon photodiode S3477-04 (Hamamatsu Photonics) were used for the comparison measurements in the wavelength ranges 290-400 nm and 450-900 nm, respectively. The bandwidth of the spectroradiometer was 4.8 nm for both cases. Three different cut-off filters were used for the wavelength ranges 290-380 nm, 390-650 nm, and 700-900 nm.

The measurements were composed of two steps. The first step was to transfer the scale from the three NIMT primary standard lamps into two NIMT reference lamps. This step was done by placing the NIMT primary standard lamp and the NIMT reference lamp on the opposite

sides of the spectroradiometer entrance stage consisting of a rotating diffuser plate in the middle (see Fig. 2). A calibrated rafter square ruler was used for the alignment and in defining the optical axis.

The second step of the comparison measurements was to transfer the scale from the two NIMT reference lamps to the three MIKES transfer standard lamps. In this step, the NIMT primary standard lamp was removed from the stage and replaced by the transfer standard lamp. Since the NIMT lamps and the MIKES lamps were of different type, the alignment procedure was slightly modified for the MIKES lamps. The optical axis of the measurement was defined by the NIMT alignment laser which was used to transfer the position of the optical axis to the dual-beam alignment laser. Each transfer standard lamp was then aligned perpendicular to the optical axis. The distance from the spectroradiometer entrance aperture was adjusted using a calibrated length rod. No baffles were used between the MIKES lamps and the spectroradiometer entrance aperture, since stray light is minimized by absence of any large reflecting surfaces close to the lamps. Furthermore, the laboratory walls are painted matt black to reduce the effect of stray light.

The uncertainty budget for the NIMT calibration measurements is given in Table 1 for different wavelength ranges. The main uncertainty component comes from the traceability of the NIMT primary standard lamps. The uncertainties related to the reproducibility are based on measurements with new alignments and burns of the compared lamps. The reproducibility of the comparison run is estimated from altogether 8 measurements with completely new alignment of either the MIKES transfer standard lamp or the NIMT reference lamp. The uncertainty components related to reproducibility are of type A while all other uncertainty components are of type B.

The distance setting uncertainties of NIMT and MIKES lamps are based on rectangular uncertainty distributions of full widths 1 mm and 2 mm, respectively. A small systematic bias in the distance setting of the reference lamp would not affect the calibration of the MIKES lamp and thus the corresponding uncertainty component is not included in Table 1. Only the reproducibility of the distance setting of the reference lamp matters, but this is already taken into account by the reproducibility components of Table 1. The standard uncertainty of the primary standard lamp voltage setting is 3 mV and that of the transfer standard lamp current setting is 0.4 mA. The uncertainty component due to the wavelength scale of the spectroradiometer is calculated on the basis of the standard uncertainty between 0.1 nm and 2.5 nm depending on wavelength. The uncertainty due to ageing of the NIMT lamps is based on the recorded burn hours since the previous calibration and the measured [5] ageing rate of similar lamps in actual operating conditions. The full width of the rectangular probability distribution is taken as twice the applied correction, because there is not yet ageing data available for the NIMT lamps used. The combined

standard uncertainty u_α of NIMT measurements at the different comparison wavelengths is listed in Table 2 in the next section.

Table 1. Uncertainty budget for measurements at NIMT.

Component	Relative Standard Uncertainty in Spectral Irradiance (%)			
	290-400 nm	450-550 nm	600-800 nm	850-900 nm
NIMT Scale	2.40	1.40	1.80	3.00
Reproducibility of Scale Transfer to Reference Lamp	0.34	0.24	0.22	0.26
Reproducibility of Comparison Run	0.71	0.43	0.29	0.13
Distance setting (Primary Lamp)	0.12	0.12	0.12	0.12
Distance setting (Transfer Lamp)	0.23	0.23	0.23	0.23
Voltage setting (Primary Lamp)	0.01	0.01	0.01	0.01
Current setting (Transfer Lamp)	0.08	0.06	0.04	0.02
Wavelength	0.28	0.11	0.04	0.04
Ageing (Primary Lamp)	0.05	0.05	0.05	0.05
Ageing (Reference Lamp)	0.09	0.09	0.09	0.09
Quadratic sum	2.55	1.51	1.86	3.03

5. Results

5.1. Uncertainties due to linking

Figure 3 shows the difference in the MIKES calibration results of 2006 and 2008. The difference is compatible with the dashed lines indicating the uncorrelated uncertainty $u_{uc,i}$ of MIKES [1]. The two lamps that stayed at MIKES show a similar change in spectral irradiance as the three transfer standard lamps indicated by filled symbols. The differences between the largest and smallest lamp

voltages at the end of the measurements at MIKES and NIMT are 30 mV, 90 mV, and 20 mV for lamps 245, 257, and 313, respectively. Thus there are no indications that spurious changes would have occurred in the transfer standard lamps during the comparison measurements.

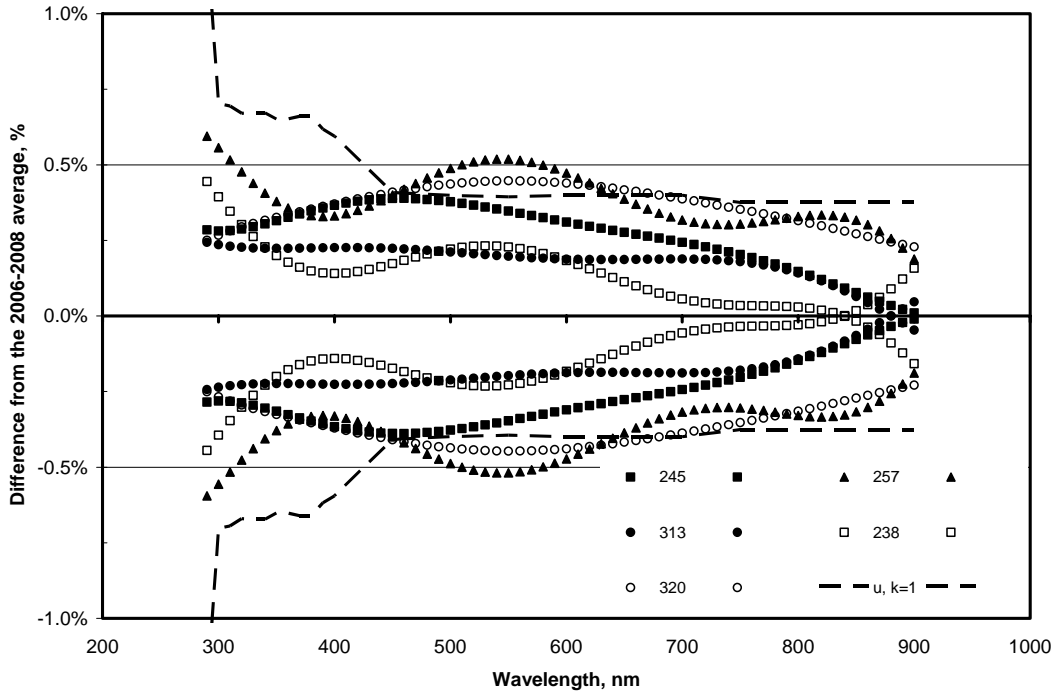


Figure 3. Difference of the MIKES calibrations using the spectral irradiance scales from two subsequent realizations from 2006 (predominantly positive values) and from 2008 (predominantly negative values). The lamps marked with filled symbols were transported to NIMT and back, while the ones marked with open symbols stayed at MIKES. The dashed lines indicate the standard uncertainty based on uncorrelated uncertainty components of MIKES.

In the measurements at MIKES, a baffle with 10-cm opening was used between the lamp and the filter radiometer, whereas NIMT used no baffle. The uncertainty component due to presence/absence of the stray-light reducing baffle was studied at the MIKES setup by auxiliary measurements without the baffle using 302 nm, 352 nm, 599 nm, and 902 nm band-pass filters. No systematic effect was found within the relative standard uncertainty of $u_{bc} = 0.17\%$ resulting from the estimated rectangular probability distribution of 0.6% full width.

Columns two and three in Table 2 list the standard uncertainty u_{α} of the NIMT measurements and the uncorrelated uncertainty $u_{uc,i}$ of MIKES measurements [1], respectively. The standard uncertainty $u_{b,i}$ of the bilateral comparison in Table 2 consists of the uncertainty u_{bc} and of the contribution from the link NMI uncorrelated uncertainty as shown in Eq. (A2). Uncertainty components such as the current and distance setting of the transfer standard lamps are included in the NIMT uncertainty budget.

Table 2. Standard uncertainties of NIMT (u_{α}), uncorrelated uncertainties of MIKES ($u_{uc,i}$), uncertainties of the bilateral comparison ($u_{b,i}$), uncertainties of MIKES including the long-term reproducibility of the scale ($u_{r,i}$), uncertainties of KCRV [$u(x_{ref})$], and transfer uncertainties of the CIPM key comparison (u_{kc}) as a function of wavelength.

Wavelength [nm]	u_{α}	$u_{uc,i}$	$u_{b,i}$	$u_{r,i}$	$u(x_{ref})$	u_{kc}
290	2.55	1.24	0.90	1.86	0.30	0.25
300	2.53	0.70	0.52	1.05	0.28	0.26
310	2.51	0.69	0.52	1.04	0.26	0.30
320	2.52	0.68	0.51	1.01	0.25	0.27
330	2.53	0.67	0.50	1.01	0.24	0.24
340	2.54	0.67	0.50	1.01	0.24	0.23
350	2.53	0.65	0.49	0.98	0.23	0.22
360	2.53	0.65	0.49	0.98	0.22	0.20
370	2.53	0.66	0.50	0.99	0.22	0.19
380	2.52	0.66	0.50	0.99	0.22	0.18
390	2.51	0.62	0.47	0.93	0.21	0.17
400	2.49	0.60	0.45	0.89	0.20	0.18
450	1.51	0.41	0.33	0.41	0.17	0.22
500	1.49	0.40	0.33	0.40	0.16	0.20
550	1.50	0.39	0.33	0.39	0.15	0.20
600	1.86	0.40	0.33	0.40	0.15	0.18
650	1.85	0.40	0.33	0.40	0.15	0.16
700	1.85	0.40	0.33	0.40	0.15	0.14
750	1.84	0.38	0.32	0.38	0.15	0.13
800	1.84	0.38	0.32	0.38	0.15	0.13
850	3.03	0.38	0.32	0.38	0.15	0.18
900	3.02	0.38	0.32	0.38	0.15	0.14

The uncertainty component related to the reproducibility of the link NMI results of the two comparisons is denoted by $u_{r,i}$. For this bilateral comparison it was possible to obtain information on the uncertainty related to the MIKES scale reproducibility, $u_{r,i}$, with the help of an informal comparison with A*STAR, Singapore [6]. The scale of A*STAR is linked to the key comparison reference value (KCRV) via a bilateral comparison CCPR-K1.a.1 with NMIA, Australia [7]. An estimate for the combined long-term changes of the spectral irradiance scales of MIKES and A*STAR can be obtained by comparing the scale differences in the informal comparison and via CCPR-K1.a/CCPR-K1.a.1. In the wavelength range 450-900 nm the results of the informal comparison [6] and key comparison [1,7] are well in agreement within the uncertainties calculated on the basis of uncorrelated uncertainties of the NMIs, whereas for the

wavelength range 290-400 nm the average scale change of 2 % is somewhat larger than the average standard uncertainty of 1.3 %. Multiplication of the uncorrelated uncertainties by a factor of 1.5 restores approximate agreement with the assumption that the scales of MIKES and A*STAR have not changed between 2003 and 2008. Accordingly, Table 2 lists values $u_{r,i} = 1.5 \times u_{uc,i}$ for the spectral range 290-400 nm and $u_{r,i} = u_{uc,i}$ for the spectral range 450-900 nm.

Table 2 also shows the approximate uncertainty of the KCRV, $u(x_{ref})$, and the transfer uncertainty of the key comparison, u_{kc} . The latter uncertainty is obtained from the final report of the CCPR-K1.a as the artifact instability uncertainty [1]. The weight of MIKES is $w_i \approx 0.1$. With the parameters of Table 2, Eqs. (A1) and (A3) can be used to calculate the uncertainties of the degrees of equivalence of NIMT.

5.2. Results of the bilateral comparison

The NIMT and MIKES results of spectral irradiance for the three transfer standard lamps are listed in Appendix B. Figure 4 shows the relative difference between the NIMT and MIKES results. The expanded uncertainty ($k = 2$) has been calculated as $2(u_\alpha^2 + u_i^2 + u_{bc}^2)^{1/2}$, where u_i is the standard uncertainty of the measurements at MIKES. In Fig. 5, the average relative difference between the NIMT results and the KCRV is plotted with the expanded uncertainty calculated using Eq. (A1). This is the main result of the bilateral comparison quantifying the unilateral degrees of equivalence of NIMT at the different wavelengths. Numerical values of the degrees of equivalence with the corresponding uncertainties are listed in Appendix C.

Use of Eq. (A3) is illustrated by calculating the uncertainty of the degrees of equivalence between NIMT and NMIJ as shown in Fig. 6. NMIJ is the source of traceability for NIMT and thus u_j in Eq. (A3) is taken as the uncorrelated uncertainty of NMIJ as listed in the final report of CCPR-K1.a [1]. This avoids double counting of the correlated uncertainty components of NMIJ since they are already included in the spectral irradiance scale uncertainty of NIMT.

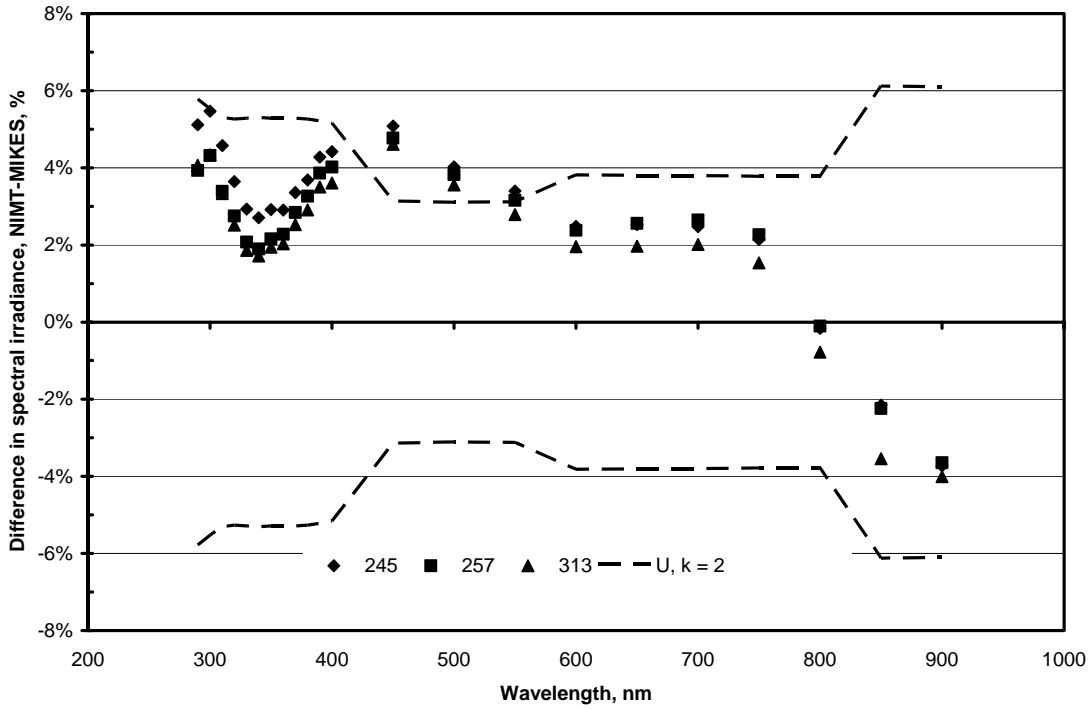


Figure 4. Relative difference of the spectral irradiance values measured by NIMT and MIKES for the three transfer standard lamps.

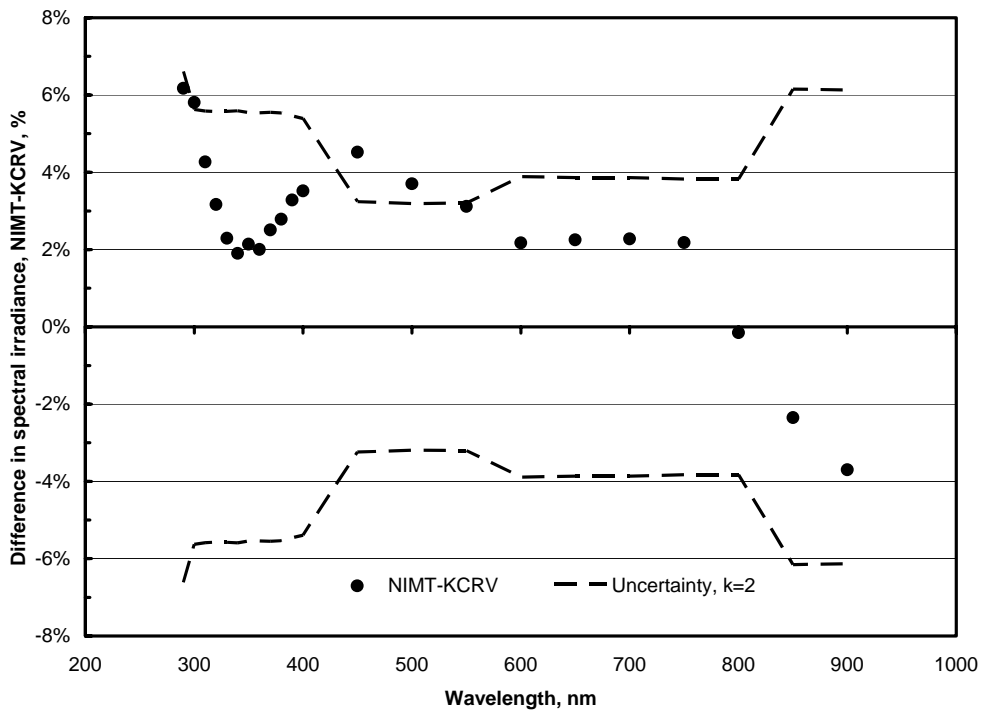


Figure 5. Degrees of equivalence of NIMT at different wavelengths. Calculation of the expanded uncertainty is based on Eq. (A1).

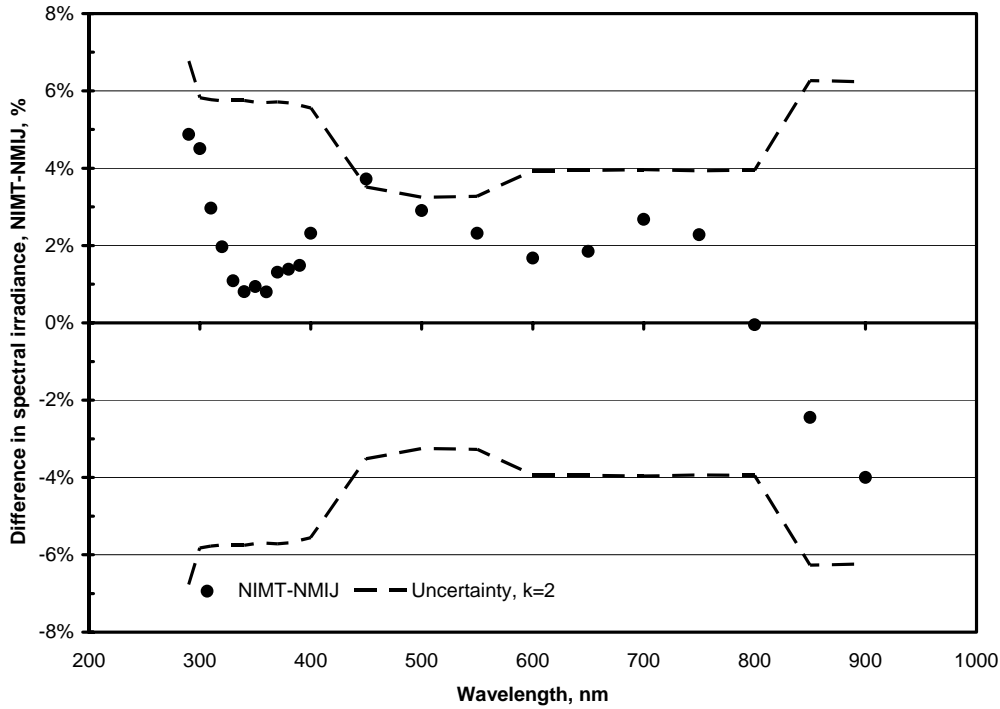


Figure 6. Mutual degrees of equivalence between NIMT and NMIJ at different wavelengths. Calculation of the expanded uncertainty is based on Eq. (A3).

6. Conclusions

The NIMT spectral irradiance scale is traceable to NMIJ. The results of the bilateral comparison emphasize the importance of comparison measurements even in the case where an NMI takes traceability from another NMI. NIMT found a deviation at 450 nm wavelength which may indicate an unknown effect related to the change of the detector of the spectroradiometer close to that wavelength. At all other wavelengths, the NIMT results were acceptable within the uncertainty of the mutual degree of equivalence between NIMT and NMIJ.

Appendix A. Uncertainties in linking comparison results

NMI α that has not participated in the CIPM key comparison wishes to link their measurements to the KCRV through NMI i with a bilateral comparison. The uncertainty of the unilateral degree of equivalence $D_{\alpha(i)}$ of NMI α via NMI i is then [8,9]

$$u^2(D_{\alpha(i)}) = u_{\alpha}^2 + u^2(x_{\text{ref}}) + (1 - 2w_i)u_{\text{kc}}^2 + u_{b,i}^2 + u_{r,i}^2 \quad , \quad (\text{A1})$$

where u_{α} is the standard uncertainty of the measurements at NMI α , $u(x_{\text{ref}})$ is the uncertainty of KCRV, u_{kc} is the transfer uncertainty of the CIPM key comparison, and w_i is the weight of NMI i in calculating the KCRV. Parameter

$$u_{b,i}^2 = u_{\text{bc}}^2 + u_{\text{uc},i}^2/2 \quad (\text{A2})$$

is the standard uncertainty of the bilateral comparison consisting of the uncertainty u_{bc} corresponding to the transfer error and of the contribution by the uncorrelated uncertainty components $u_{\text{uc},i}$ of the link NMI. The uncertainty component related to the reproducibility of the link NMI results in the two comparisons is denoted by $u_{r,i}$. The uncertainty of the mutual degree of equivalence between NMI α and another key comparison participant NMI j ($i \neq j$) is [8,9]

$$u^2(D_{\alpha j}) = u_{\alpha}^2 + u_j^2 + 2u_{\text{kc}}^2 + u_{b,i}^2 + u_{r,i}^2, \quad (\text{A3})$$

where u_j is the standard uncertainty of the measurements at NMI j .

Appendix B. Measurement results of NIMT and MIKES

NIMT results

Spectral irradiance [$\text{W m}^{-2} \text{nm}^{-1}$]

Wavelength [nm]	Spectral irradiance [$\text{W m}^{-2} \text{nm}^{-1}$]			Uncertainty, k = 1
	BN-9101-245	BN-9101-257	BN-9101-313	[%]
290	9.40E-04	1.20E-03	1.04E-03	2.55
300	1.39E-03	1.76E-03	1.53E-03	2.53
310	1.96E-03	2.46E-03	2.15E-03	2.51
320	2.69E-03	3.36E-03	2.94E-03	2.52
330	3.61E-03	4.46E-03	3.93E-03	2.53
340	4.76E-03	5.83E-03	5.16E-03	2.54
350	6.16E-03	7.50E-03	6.65E-03	2.53
360	7.81E-03	9.45E-03	8.42E-03	2.53
370	9.78E-03	1.18E-02	1.05E-02	2.53
380	1.20E-02	1.44E-02	1.29E-02	2.52
390	1.47E-02	1.74E-02	1.57E-02	2.51
400	1.75E-02	2.07E-02	1.87E-02	2.49
450	3.65E-02	4.22E-02	3.87E-02	1.51
500	6.09E-02	6.95E-02	6.45E-02	1.49
550	8.86E-02	9.97E-02	9.35E-02	1.50
600	1.16E-01	1.29E-01	1.22E-01	1.86
650	1.42E-01	1.56E-01	1.49E-01	1.85
700	1.63E-01	1.79E-01	1.71E-01	1.85
750	1.80E-01	1.95E-01	1.88E-01	1.84
800	1.88E-01	2.03E-01	1.96E-01	1.84
850	1.91E-01	2.05E-01	1.98E-01	3.03
900	1.91E-01	2.04E-01	1.99E-01	3.02

MIKES results

Wavelength [nm]	Spectral irradiance [$\text{W m}^{-2} \text{nm}^{-1}$]			Uncertainty, $k = 1$ [%]
	BN-9101-245	BN-9101-257	BN-9101-313	
290	8.941E-04	1.157E-03	9.975E-04	1.35
300	1.316E-03	1.685E-03	1.463E-03	1.10
310	1.876E-03	2.379E-03	2.077E-03	0.85
320	2.599E-03	3.266E-03	2.866E-03	0.75
330	3.510E-03	4.372E-03	3.855E-03	0.75
340	4.632E-03	5.722E-03	5.068E-03	0.75
350	5.986E-03	7.337E-03	6.526E-03	0.75
360	7.590E-03	9.236E-03	8.249E-03	0.75
370	9.462E-03	1.143E-02	1.025E-02	0.75
380	1.161E-02	1.394E-02	1.255E-02	0.75
390	1.405E-02	1.677E-02	1.514E-02	0.70
400	1.678E-02	1.992E-02	1.804E-02	0.65
450	3.469E-02	4.029E-02	3.701E-02	0.40
500	5.853E-02	6.692E-02	6.225E-02	0.40
550	8.566E-02	9.667E-02	9.092E-02	0.40
600	1.130E-01	1.260E-01	1.197E-01	0.40
650	1.380E-01	1.522E-01	1.457E-01	0.40
700	1.592E-01	1.739E-01	1.676E-01	0.40
750	1.758E-01	1.908E-01	1.849E-01	0.40
800	1.879E-01	2.029E-01	1.974E-01	0.40
850	1.954E-01	2.101E-01	2.052E-01	0.40
900	1.984E-01	2.120E-01	2.077E-01	0.40

Appendix C. Unilateral degrees of equivalence

Unilateral degrees of equivalence of NIMT with the corresponding expanded uncertainties ($k = 2$).

Wavelength [nm]	DoE [%]	$U(\text{DoE})$ [%]
290	6.2	6.6
300	5.8	5.6
310	4.3	5.6
320	3.2	5.6
330	2.3	5.6
340	1.9	5.6
350	2.1	5.5
360	2.0	5.5
370	2.5	5.6
380	2.8	5.5
390	3.3	5.5
400	3.5	5.4
450	4.5	3.2
500	3.7	3.2
550	3.1	3.2
600	2.2	3.9
650	2.2	3.9
700	2.3	3.9
750	2.2	3.8
800	-0.2	3.8
850	-2.3	6.2
900	-3.7	6.1

References

- [1] Woolliams E R, Fox N P, Cox M G, Harris P M and Harrison N J 2006 Final report on CCPR-K1.a: Spectral irradiance from 250 nm to 2500 nm, *Metrologia* **43** (Tech. Suppl.)
- [2] Kūbarsepp T, Kärhä P, Manoocheri F, Nevas S, Ylianttila L and Ikonen E 2000 Spectral irradiance measurements of tungsten lamps with filter radiometers in the spectral range 290 nm to 900 nm *Metrologia* **37** 305-12
- [3] Kärhä P, Toivanen P, Manoocheri F and Ikonen E 1997 Development of a detector-based absolute spectral irradiance scale in the 380-900-nm spectral range *Appl. Opt.* **36**, 8909-18
- [4] NIMT spectral irradiance scale, <http://www.nimt.or.th/nimt/upload/linkfile/sys-metrology-289-163.pdf>
- [5] Ylianttila L, Jokela K and Kärhä P 2003 Ageing of DXW-lamps *Metrologia* **40** S120-3
- [6] Liu Y J, Xu G, Ojanen M and Ikonen E 2008 Spectral Irradiance Comparison Using a Multi-Wavelength Filter Radiometer, *Proceedings of NEWRAD 2008 Conference*
[http://newrad2008.kriss.re.kr/program/pdf/\[TU_O_07\]Spectral_Irradiance_Comparison_Using_a_Multi-Wavelength_Filter_Radiometer_Yuanjie_Liu.pdf](http://newrad2008.kriss.re.kr/program/pdf/[TU_O_07]Spectral_Irradiance_Comparison_Using_a_Multi-Wavelength_Filter_Radiometer_Yuanjie_Liu.pdf)
- [7] Wilkinson F, Xu G and Liu Y J 2006 Final report on CCPR-K1.a.1: Bilateral comparison of spectral irradiance between NMIA (Australia) and SPRING (Singapore) *Metrologia* **43** (Tech. Suppl)
- [8] Ikonen E, Hovila J and Park S N 2006 Uncertainties in linking bilateral and regional key comparisons to the CCPR key comparison, presented at the 2nd CIE Expert Symposium on Measurement Uncertainty (Braunschweig, Germany)
- [9] Ojanen M, Shpak M, Kärhä P, Leecharoen R, and Ikonen E, Uncertainty analysis for linking a bilateral key comparison to the CCPR key comparison: spectral irradiance comparison between MIKES (Finland) and NIMT (Thailand), to be published