APMP Comparison on Luminous Flux Units (APMP.PR-K4)

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Abstract

During the 18th APMP meeting in 2004, TCPR agreed that the luminous flux should be one of the several regional comparisons to be conducted in the field of photometry and radiometry, and the project was named as APMP.PR-K4.

Nine laboratories took part in this comparison. A group of LF 200W lamps (no less than three) was used as transfer artifacts by each participant. The National Institute of Metrology (China) acted as the pilot laboratory.

Presented in this report are the detailed procedures and results of the work.

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1. Introduction

1.1 The latest CCPR Key Comparison of luminous flux was completed in 1997. BIPM and 16 NMI's joined in the comparison, including 4 NMI's of APMP CSIRO(now NMIA), CSIR(now NMISA), ETL(now NMIJ/AIST) and NIM.
1.2 At the APMP TCPR meeting held in 2004, it was agreed that the National Institute of Metrology (NIM) act as the pilot laboratory in an APMP luminous flux comparison. The aim of this regional comparison is to form a link between the Key Comparison Reference Value (KCRV) of CCPR-K4 and luminous flux scales of APMP laboratories that had not participated in the CCPR Key Comparison theretofore.
1.3 This comparison was carried out according to a technical protocol approved by all the participating laboratories and WG-KC, registered as regional comparison APMP PR-K4.
1.4 This report describes the principle and procedures of the comparison, the participating laboratories including the pilot laboratory，the measurement results, linkage with the CCPR key comparison K4(1997) and equivalence of the two comparisons. Degrees of equivalence to the CCPR K4 KCRV are derived.

2. Participants, Transfer Standards and Operational conditions

2.1 List of Participants

In table 1 the participating laboratories are listed with their acronyms in the first column, the name of the laboratories in the second column, the economies they belong to in the third column, and the number of the lamps which were used as transfer standards in the last column.

Table 1 Participants of the APMP luminous flux comparison

Acronym	Laboratory name	Economy	Number of lamps
CMS	Center for Measurement Standards	Chinese Taipei	3
NMISA)1	National Metrology Institute of South Africa	South Africa	4*
KRISS	Korea Research Institute of Standards and Science	South Korea	3
NIMT	National Institute of Metrology	Thailand	3
NMIJ/AIST)2	National Metrology Institute of Japan	Japan	3*
NML-SIRIM)3	National Metrology Laboratory, SIRIM Berhad	Malaysia	3
NPLI	National Physical Laboratory	India	3
NMC-A*STAR)4	National Metrology Centre ,Singapore	Singapore	3

NIM	National Institute of Metrology	China	7*

)1 Named as CSIR at the 1997 CCPR key comparison CCPR K4.

)2 Named as ETL at the 1997 CCPR key comparison CCPR K4.

)3 The pilot laboratory supplied 3 lamps for NML-SIRIM as transfer lamp.

)4 Formerly named as SPRING .

* Participants of the 1997 CCPR key comparison CCPR K4

2.2 Transfer Standards and Transportation

Polaron type LF 200W lamps as used in the 1997 CCPR K4 comparison were chosen to be the transfer standards in this comparison. Each participant was to use a batch of transfer standards comprising of at least 3 lamps with a distribution temperature of 2750±50 K. The pilot laboratory provided 3 Polaron type LF 200W lamps as transfer standards for participants who don't own a batch of this kind of lamp. Only one participant, NML-SIRIM, used NIM's transfer standard.

In the technical protocol of this comparison "hand-carrying" was recommended as the way of transporting the transfer standards and each participant would have to do two trips. Four participants NMISA, KRISS, NIMT and NMC-A*STAR transported their lamps by hand, others used the public transportation system. The filament hook of one lamp of NMC-A*STAR became disconnected from its supports during transport, but by comparing the initial measurement results with the returned results from NMC-A*STAR, the performance of the lamp was proved to be stable, so the results of this lamp were still included in the final results.

Figure 1 Polaron type LF 200W Lamp

2.3 Operational Conditions

Electric power supply: The transfer standards were operated at an individual current, given by the owner laboratory, so that the distribution temperature was (2750±50)K. The transfer standards mount in an E27 holder with the cap up. The electrical power supply was DC with the lamp current measured as the voltage across a standard resistance using a DVM. It was operated with a random polarity. The lamp current was to be ramped up slowly over about 1 min to the required value and photometric measurements were made after the lamp had been stabilized (7 minutes to 10 minutes after turning on) .The lamp voltage was measured at the vicinity of the cap using four-pole technique. After measurement the electrical power supply was ramped down slowly in about 1 minute.

Thermodynamic conditions: The transfer standard is an incandescent lamp which is not very sensitive to environment condition, such as ambient temperature, humidity, etc. The suggested measurement conditions mainly include a temperature of 20 °C to 25 °C, a humidity less than 70% RH, and a variation of temperature less than ± 1 °C. The exact temperature and humidity of the laboratory at the period of the measurements were to be reported as operational conditions. At the Pilot laboratory, the temperature of the photo-detector was controlled at (25±1) °C by adjusting the environmental temperature during the measurement period.

3. Form of comparison

3.1 Method of comparison

3.1.1 NIM acted as the pilot laboratory. Most participants prepared a batch of lamps of their own as transfer standard except NML-SIRIM who used transfer lamps of NIM.

3.1.2 The comparison acted as a star type. Following this procedure, laboratories using their own transfer standards measured their lamps before shipped to NIM, together with the initial measurement results. All the shipped lamps and NIM's transfer standards for NML-SIRIM were measured together at NIM, after that the transfer standards were sent to the participants for re-measure. NML-SIRIM shipped the transfer standards to NIM after their measurement, then NIM re-measured these transfer standards.

3.2 Schedule

The comparison was delayed for various reasons, mainly due to some of the participants needing more time to prepare the artifacts, and delays also occured in the transportation.

Table 2 Timeline schedule of luminous flux comparison

Activity	Time	Comment
Invitation to participate	June 2005	
Receiving the response from participants	September 2005	Each participant should clarify whether they will use NIM's transfer standard or its own; Confirm a schedule.
Full protocol approved	September 2006	Reviewed and approved by expert of WG-KC.

The transfer standards of NMISA, NMIJ/AIST, NMC-A*STAR and NIM (for NML-SIRIM) are measured in the pilot laboratory.	January 2007 ~February 2007; All the transfer standards send back to the participant before middle of July 2007.	All the transfer standards were measured five times except two lamps measured seven times, as they were unstable.
The transfer standards of CMS, KRISS, NIMT, and NIM were measured in the pilot laboratory.	Beginning of August 2007~ middle of August 2007. All the transfer standards were sent back to the participant before the end of Sep. 2007.	All the transferred standards were measured four times.
The transfer standards of NPLI were measured at the pilot laboratory.	Middle of November 2007~ end of November 2007.	NPLI lamps delayed about three months in customs.

4. Measurements

The luminous flux of each lamp was measured at least 2 independent times. Each independent time included more than one set of measurements, in which the lamp and facilities were reinstalled. A complete set included repeat measurements on the same lamp at the participant laboratory to obtain the appropriate accuracy as limited by the noise characteristics of their specific measurement facility. In the measurement report only the mean of the final declared values was to be included. Participants were reminded that the luminous flux of the transfer standard lamps will change with the operational burn time and so it was recommended that this be kept to a minimum, and the burn time be reported to the pilot laboratory.

In pilot laboratory (NIM), the measurements were carried out with complete substitution method using an integrating sphere photometer, which cancels out some of the systematic errors, providing the instrumentation is stable over the duration of the comparison. Each lamp was measured at least 4 times within the campaign, at each time two sets of measurement were made, and the photocurrent for one measurement was averaged from 10 readings. During the comparison, the stability of the NIM measurement setup was monitored with a batch of monitor lamps, and the reading changes of the monitor lamps were used to verify the photocurrent response of the photometer.

The distribution temperature of each participant's lamps was also checked by the pilot laboratory (NIM).

5. The measurement facility at NIM

5.1Basis of the luminous flux scale

The facility of realizing candela at NIM consist of a group of seven electrically calibrated radiometers with conical cavity, precision aperture, high quality V(λ) filters and secondary standard luminous intensity lamp. The luminous flux unit is based on an independent realization by means of goniophotometer, which is traced to the luminous intensity scale.

5.2 Description of the NIM integrating sphere photometer

An integrating sphere photometer, shown in Fig. 2, was used in this comparison with 2 m diameter. The diameter of the baffle is about 240 mm and the distance from the

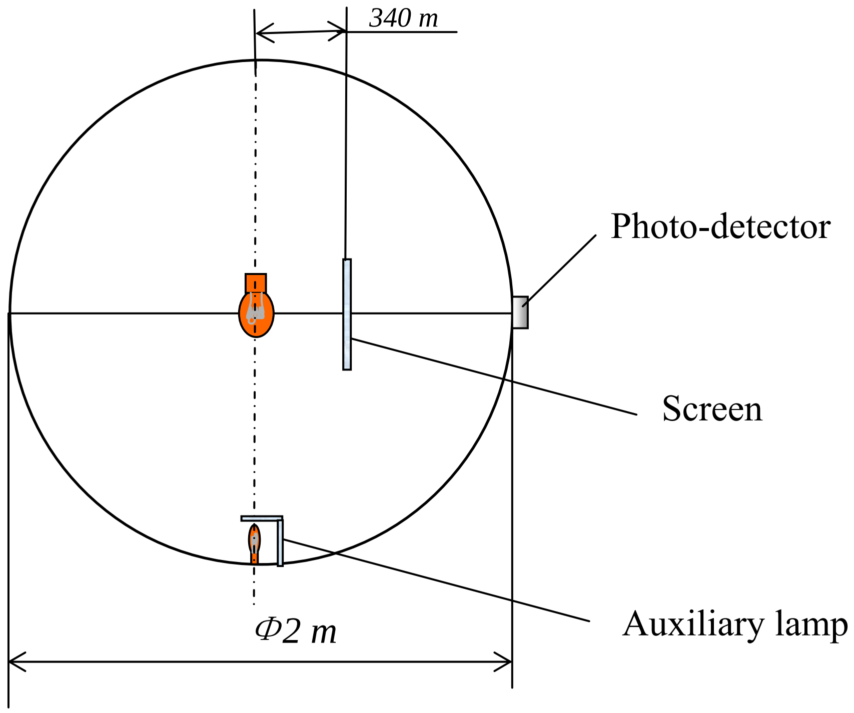

Figure 2 The Integrating sphere photometer of NIM

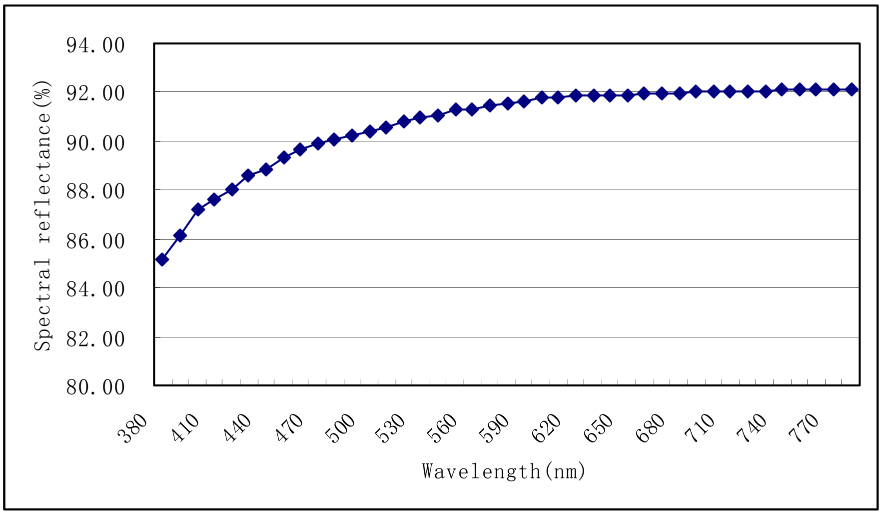

Figure 3 Spectral reflectance of the inner coating of NIM's integrating sphere

baffle to centre of the integrating sphere is about 340 mm. The sphere is coated with

$BaSO_4$ having a spectral reflectance about 90%, as shown in Fig. 3. The photo-detector is made by Inphora with V(λ) filter , cosine adapter, f_1' of 1.5%, and a temperature sensor is located very close to the photo-detector to monitor its temperature. An auxiliary lamp located at the bottom of the sphere.

The spectral reflectance of the inner coating of the sphere is shown in Fig. 3.

5.3 The spectral mismatch correction

In this comparison, the distribution temperature of all the transfer standards are within the range of 2725 K to 2799 K, and a spectral mismatch correction was made to every lamp according to its distribution temperature. The relationship of the distribution temperature of the transfer standard versus the spectral mismatch correction factor is shown in Fig 4.

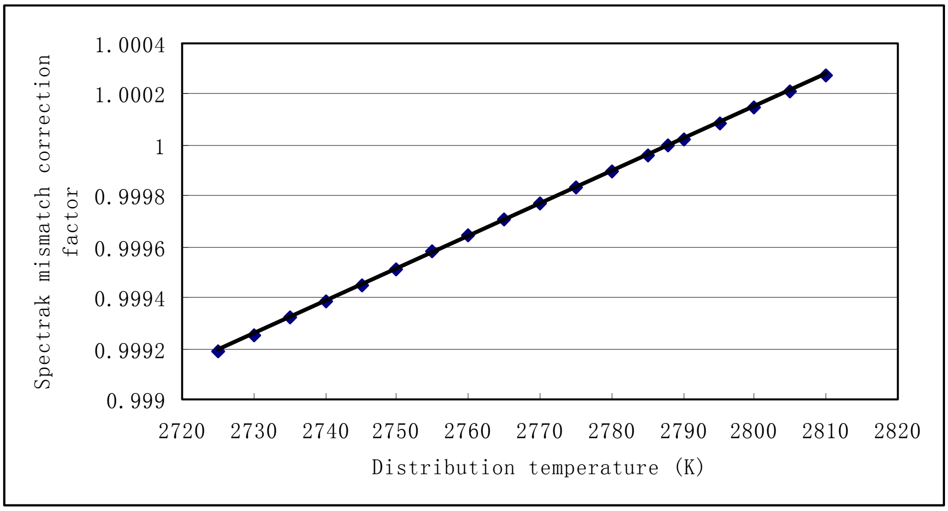

Figure 4 Spectral mismatch correction factor vs. the distribution temperature

5.4 Nonlinearity

NIM nonlinearity measurement equipment is set up based on the conjoined-beam method. Beams were established with a tungsten lamp and a beam splitter, separately and then added. The measurement results are shown in Table 3 as count rates from the photometer. The count rate of the integrating sphere photometer of NIM for the LF200 lamp was 5000-6000, so nonlinearity correction was not required for the response of the photometer.

Table 3 Nonlinearity of the NIM photometer

Count rate Beam 1	Count rate Beam 2	Count rate of beam1 and beam2 conjoined	Nonlinearity correction factor
4003	4004	8007	1.0000
8010	8005	16016	0.99994

5.5 Absorption correcting factor

The integrating sphere has an auxiliary lamp at the bottom of the sphere, with a small baffle located before the auxiliary lamp. The LF 200W lamp has two kinds of base, one with and one without electroplated chromium. They show different absorption factors in the integrating sphere The absorption correcting factor of the one with chromium is about 1.00357 , and the one without chromium is about 1.00471 .The absorption factor of each lamp was measured twice in NIM, and the average was used to correct the photometer reading.

5.6 Uncertainty budget

The candela is realized by an electrically calibrated radiometer at NIM, with a group of BDQ7 and BDQ8 gas-filled tungsten-filament lamps developed as secondary standards for maintenance of the unit. The luminous flux unit lumen is derived from the candela by a goniophotometer on a batch of luminous flux lamps including 11 LF 200 lamps. These 11 LF 200 lamps were used to maintain the luminous flux unit. A batch of 7 LF 200 working standards was calibrated in a 2 m integrating sphere photometer, and used in this comparison making a link to the CCPR K4 comparison. The uncertainty budget for the NIM measurements is shown in Table 4.

Table 4 Uncertainty budget for the working standard lamps of NIM

	Source of Uncertainty	Type	Relative standard uncertainty %
1	Uncertainty of the primary standard	B	0.21
2	Repeatability of the measurement	A	0.04
3	Stability of the primary standard	B	0.04
4	Lamp Current measurement	B	0.06
5	Repeatability of the working standard lamps	A	0.07
6	V(λ) mismatch	B	<0.05
	Combined relative standard uncertainty %		**0.24**

6. Results of the participants

6.1 CMS

Basis of the luminous flux scale: NIST standard lamp (Lamp type: GE 199W, current: 1.63215 A, Voltage: 120.182 V, luminous flux: 3184 lm, distribution temperature 2850 K).

Description of the measurement facility to calibrate the transferred standard:
An integrating sphere is used as the transfer facility, with a diameter of 167 cm, and the diameter of baffle is 11.5 cm; the distance from the baffle to the integrating sphere centre is 36.5 cm, the integrating sphere coating is $BaSO_4$.
The detector is made by LMT, with f_1': 1.4 %.

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Table 5 Uncertainty budget of CMS

	Source of uncertainty	**Value of relative standard uncertainty (%)**		
	Lamp No.	P560	P563	P587
1	Realization and maintenance of unit of luminous flux	0.72	0.72	0.72
2	Transfer uncertainty	0.19	0.03	0.03
3	V(λ) mismatch correction	0.02	0.02	0.03
4	Lamp current regulation uncertainty	0.03	0.03	0.04
5	Absorption correction	0.10	0.10	0.10
6	Repeatability of luminous flux of lamp	0.11	0.10	0.14
7	Non-linearity of the photometer	0.01	0.01	0.01
	Combined relative standard uncertainty(%) of luminous flux of transfer standard lamps (k=1)	0.76	0.74	0.75

Measurement condition: Temperature:(23±1.5) °C Humidity : (45±10)% R.H

Table 6 Measurement Result of CMS

Lamp No.	**Current (A)**	**Initial**			**Return**		
		Voltage (V)	**Luminous flux(lm)**	**Distribution Temperature(K)**	**Voltage (V)**	**Luminous flux(lm)**	**Distribution Temperature(K)**
560	1.91407	86.070	2040	2761	86.217	2035	2770
563	1.89612	88.030	2040	2747	88.130	2039	2785
587	1.87403	89.134	1940	2725	89.219	1940	2748

6.2 NMISA

Basis of the luminous flux scale: A room temperature absolute radiometer fitted with a V(λ) filter and precision aperture, using an incandescent lamp, forms the basis of the realization of the candela at the NMISA. The measurement is transferred to a photometer, which is used to calibrate luminous intensity standard lamps. The lumen is derived from the candela by a goniophotometer and maintainted by a network of 6 primary standard lamps and 6 working standards.
Description of the measurement facility to calibrate the transferred standard: The goniophotometer consists of a main beam,4.2 meters in length, which is driven by a DC motor to rotate around a horizontal axis through its centre. One arm of the beam carries the photometer head, while the lamp to be measured is placed on a stationary structure at the centre of the revolving arm. The effective lamp-detector distance is 1.7 m. A LMT photometer with a spectral response approximating the V(λ) function was used, with f_1'=1.2 %.

Table 7 Uncertainty budget of NMISA
Uncertainty budget of calibration of transfer standard lamps for luminous flux using a goniophotometer

	Source of uncertainty	**Value of relative standard uncertainty (*k*=1)[%]**
1	Candela reproduced with a group of luminous intensity standard lamps	0.42
2	Transfer from luminous intensity standard	0.07
3	Repeatability of the measurements by the goniophotometer	0.06
4	Alignment of the luminous intensity standard lamp	0.04
5	Non-linearity of the photometer	0.10
6	V(λ) mismatch	0.05
7	Alignment of the test lamp	0.02
8	Lamp current regulation	0.03
9	Stray light	0.03
10	Polar angle resolution, mechanical instability and shaft speed	0.03
11	Maintenance of luminous intensity unit	0.09
12	Azimuth stepping angle	0.05
13	Weighting function	0.02
	Combined relative standard uncertainty	**0.47**

Measurement condition:
Temperature:24ºC±2°C Humidity:(50%±15%)RH

Table 8 Measurement Result of NMISA

Lamp No.	Current (A)	Initial			Return		
		Voltage (V)	Luminous flux(lm)	Distribution Temperature (K)	Voltage (V)	Luminous flux(lm)	Distribution Temperature (K)
NSF2	1.9702	91.60	2350	2734±40	91.60	2348	2734±40
NSF4	1.9703	91.89	2363	2733±40	91.89	2361	2733±40
NSF5	1.9704	89.73	2297	2733±40	89.73	2294	2733±40
NSF6	1.9703	92.50	2393	2742±40	92.50	2387	2742±40

6.3 KRISS

The luminous flux scale establishment: A set of 100 W inside-frosted tungsten lamps (not LF 200-type lamps) constitutes KRISS working standard of total luminous flux, all of which have been calibrated using the KRISS goniophotometer. The illuminance scale used in the KRISS goniophotometer is traceable to KRISS Cryogenic Radiometer.

Description of the measurement facility to calibrate the transfer standard: An integrating sphere photometer was used to calibrate the set of transfer standard lamps. The diameter of the KRISS integrating sphere is 200 cm and its detector baffle has a diameter of 30 cm. The baffle is located at 67 cm from the center of sphere. The inner surface of the sphere is coated with $BaSO_4$. The detector model is LMT P15FOT (clear window, f_1' = 2.0 %).

Table 9 Uncertainty budget of KRISS

	Source of Uncertainty	Type	Relative standard uncertainty %
1	Uncertainty of the primary standard lamp	B	0.50
2	Repeatability of the measurement	A	0.01
3	Reproducibility of the measurement	A	0.10
4	Photometer readout resolution	B	0.03
5	Temperature variation	B	0.05
6	Linearity	B	0.05
7	Lamp current	B	0.01
8	Self-absorption correction error	B	0.10
9	$V(\lambda)$, spectral mismatch correction	B	0.10
10	Spatial mismatch correction	B	0.20
	combined relative standard uncertainty		**0.58**

Measurement condition:

Temperature: (23±2) °C Humidity :≤ 55 % R.H

Table 10 Measurement Result of KRISS

Lamp No.	Current (A)	Initial			Return		
		Voltage (V)	Luminous flux (lm)	Distribution Temperature (K)	Voltage (V)	Luminous flux (lm)	Distribution Temperature (K)
P567	1.8931	88.31	2014	2753±23	88.32	2009	2753±23
P569	1.9230	90.37	2179	2753±23	90.38	2174	2750±23
P570	1.9230	91.42	2218	2753±23	91.48	2213	2749±23

6.4 NIMT

Basis of the luminous flux scale: The NIMT luminous flux scale is traceable to the realization of the SI unit of candela at NMIJ. Other influencing quantities such as electrical potential, electrical resistance and ambient temperature are metrologically traceable to the corresponding SI units through calibration with NIMT national standards which have been calibrated at either PTB or NMIJ where the realization of the units took place.

Description of the measurement facility to calibrate the transfer standard : The sphere is 2.0 meters in diameter. The inside surface of the sphere is coated with PHP 80 which has the fairly flat spectral reflectance of approximately 80 % throughout the visible region. The photometer head is made of a Si-photodiode and V(λ) filter with spectral mismatch factor, $f_1' < 1\%$, an opal glass diffuser, and a thermostat. The photo-current signal is amplified and converted to voltage signal via an external current-to-voltage amplifier unit. The self-absorption is evaluated via the use of an auxiliary lamp.

Table 11 Uncertainty Budget of NIMT

	Source of Uncertainty	Type	Relative standard uncertainty %
1	Uncertainty of the primary standard lamp	B	0.42
2	Repeatability of the measurement	A	0.04
3	Lamp Voltage measurement by the digital multi-meter	B	0.01
4	Lamp Current measurement by the digital multi-meter	B	0.10
5	Self-absorption correction factor	A	0.02
6	Aging effect of the total luminous flux of the primary standard lamp	B	0.26
7	Long-term stability of the calibration system	B	0.12
	Combined relative standard uncertainty		**0.52**

Measurement condition:

Temperature: (23±2) °C Humidity : (50±15）%

Table 12 Measurement Result of NIMT

Lamp No.	Current	Initial			Return		
		Voltage	Luminous flux	Distribution Temperature	Voltage	Luminous flux	Distribution Temperature
P572	1.9521	94.506	2512	2788	94.574	2521	2788
P573	1.9435	95.082	2507	2788	95.107	2512	2788
P574	1.9251	95.328	2495	2788	95.378	2499	2788

6.5 NMIJ/AIST

Basis of the luminous flux scale: NMIJ luminous flux scale has been derived from the NMIJ luminous intensity scale by means of goniophotometer. The NMIJ luminous intensity scale has been realized based on the illuminance responsivity scale of a photometer, which is traceable to the absolute spectral responsivity scale originated from the NMIJ electrical substitution cryogenic radiometer.

Description of the measurement facility to calibrate the transferred standard: NMIJ made all the luminous flux calibration for the transfer standard lamps by using an integrating sphere. The integrating sphere is 1.5 m in diameter and has $BaSO_4$ sprayed coating with averaged diffuse reflectance of approximately 97 % in the visible region. The diameter of the baffle in the integrating sphere is 150 mm, and the distance between the baffle and the lamp is about 300 mm. As for the auxiliary lamp, a 150 W tungsten halogen lamp is used.

Table 13 Uncertainty budget of NMIJ/AIST

Uncertainty budget for total luminous flux calibration of transfer standard lamps

	Source of Uncertainty	Type	Relative standard uncertainty %
1	Realization of the NMIJ luminous flux scale	B	0.34
2	Ageing of the working standard lamps	B	0.12
3	Self-absorption correction	A	0.04
4	Lamp current/voltage measurement	B	0.02
5	Spatial non-uniformity of the integrating sphere	B	0.07
6	Repeatability of the measurement	A	0.04
	relative combined standard uncertainty		**0.37**
	Relative expanded uncertainty(*k*=2)		**0.74**

Measurement condition: Temperature:(22.5±0. 5) °C Humidity : 40%~55% R.H

Table 14 **Measurement Result of NMIJ/AIST**

Lamp No.	Current (A)	Initial			Return		
		Voltage (V)	Luminous flux	Distribution Temperature	Voltage (V)	Luminous flux	Distribution Temperature

			(lm)	(K)		(lm)	(K)
P531	1.9446	95.558	2544.5	2788	95.574	2544.3	2788
P537	1.9474	93.787	2502.2	2788	93.824	2505.1	2788
P539	1.9494	94.461	2520.1	2788	94.493	2525.3	2788

6.6 NML-SIRIM

Basis of the luminous flux scale: The reference standard is traced to KRISS in 2007 with reference uncertainty 1.3 %.

Description of the measurement facility to calibrate the transferred standard: The calibration of a tungsten filament lamp in terms of its luminous flux is performed by comparison with a standard lamp of known luminous flux, using a 1.5 m diameter integrating sphere with silicon photodiode photometer as the transfer device. The method used is essentially one of direct substitution of the test lamp for the reference lamp. The integrating sphere with photometer is first calibrated using one of the standard lamps. After reference lamp is calibrated, replace the reference standard lamp with lamp under test. To complete the cycle, the reference lamp is calibrated again. The coating of the integrating sphere is $BaSO_4$ and the distance between the baffle and the centre of the integrating sphere is 35 cm.

The lamp used in this comparison was Polaron incandescent lamp serial number P 240 with total luminous flux value of 1077 lumen at current and voltage setting 1.1090 A and 101.54 V respectively.

Table 15 Uncertainty budget of NML-SIRIM

Source of Uncertainty	Value(%)
Ageing	0.3
Lamp used	1.3
DVM	0.001
Std. Resistor	0.05
Colour Correction Factor	0.05
Self absorption factor	0.2
Test Lamp repeatibility	0.2
Combined Expanded uncertainty	**1.5**

Measurement condition: Temperature: (24±2)^{o} C Humidity: (50±10)%RH

Table 16 Measurement Result of NML-SIRIM*

Lamp No.	Current (A)	Initial		
		Voltage (V)	Luminous Flux (lm)	Distribution Temperature (K)

P 561	1.9386	91.0	2338	/
P 562	1.9378	92.0	2357	/
P 564	1.9361	89.6	2286	/

*NML-SIRIM made five sets of measurement to determine one NIM's transfer standard value.

6.7 NPLI

Basis of the luminous flux scale: The goniophotometer is used to calibrated a group of three Polaron 200 W lamps having color temperature of approximately 2800 K. These lamps are used as primary standard to measure the luminous flux of the three transfer standards lamps (Polaron LF 200W) using the integrating sphere. The realization and maintenance of the primary scale of optical radiation is by an indigenously developed ESR (also called absolute radiometer). The luminous intensity scale is derived through these absolute radiometers.

Description of the measurement facility to calibrate the transferred standard: In the measurement an integrating sphere with a diameter of 2.5 m is used. This sphere has one observation port of approximately 40 mm diameter to mount the detector assembly and also the other port is for an auxiliary lamp. The sphere is coated with BaSO4 sphere paint having approximately nonselective spectral reflectance of 0.85. The baffles are changed according to the size and shape of the lamps. A cosine corrected silicon photo-diode with V(λ) filter is mounted at the observation port of the integrating sphere.

Table 17 Uncertainty budget of NPLI

Uncertainty budget of calibration of transfer standard lamps for luminous flux using an integrating sphere

	Source of uncertainty	**Value of relative standard uncertainty (%)**
1	Calibration of goniophotometer for illuminance scale	0.55=Sqrt[(the uncertainty of the luminous intensity lamps)^2+(the calibration of detector for illuminance responsivity)^2]
2	Repeatability of the luminous flux of the reference lamp	0.1
3	Transfer uncertainty	0.1
4	Non-linearity of photometer	0.1
5	V(λ) mismatch correction	0.1
6	Lamp current regulation and uncertainty	0.02
7	Lamp voltage statbility	0.02
8	Spectral mismatch	0.1
9	Repeatability of luminous flux of test lamp	0.1

10	Absorption correction	0.01
11	Random noise	0.1
12	Temperature variation of the detector	0.02
	Combined relative standard uncertainty (%)	**0.61**

Measurement condition:

Temperature:(24±2)°C Humidity:(50±10)%rh

Table 18 Measurement Result of NPLI

Lamp No.	Current	Initial			Return		
		Voltage	Luminous flux	Distribution Temperature	Voltage	Luminous flux	Distribution Temperature
P591	1.9467	95.15	2454	2766±20	95.15	2455	2785±20K
P592	1.9567	95.28	2566	2780±20	95.35	2568	2780±20K
P593	1.9267	95.05	2408	2779±20	95.05	2410	2784±20K

6.8 NMC-A*STAR

Basis of the luminous flux scale: NMC-A*STAR Singapore maintains the unit of luminous flux on a group of four incandescent lamps calibrated by NPL, UK. The last calibration was done in June 2006 with expanded calibration uncertainty of 0.8 % (*k*=2).

Description of the measurement facility to calibrate the transferred standard:

The integrating sphere photometer was used for the calibration of the 3 transfer standard lamps. The integrating sphere is 2 meters in diameter with 0.5 meter intermediary, and the photometer head used is thermostabilised. A baffle is placed between the lamp and the photometer head. The distance from the baffle to the integrating sphere centre is 750 mm. An auxiliary lamp for absorption correction is located opposite to the opening of the photometer head. The integrating sphere coating has a reflectance of about 95% over the visible wavelength range.

Table 19 Uncertainty budget of NMC-A*STAR

Uncertainty budget of calibration of transfer standard lamps for luminous flux using an integrating sphere

	Source of uncertainty	Value of relative standard uncertainty (%)
1.	Realization and maintenance of unit luminous flux	0.45
2	Transfer uncertainty	0.09
3	V(λ) mismatch correction	0.02
4	Lamp current regulation and uncertainty	0.05
5	Absorption correction	0.03
6	Repeatability of luminous flux of lamp	0.04
7	Non-linearity of the photometer	0.05

	Combined relative standard uncertainty (%) of luminous flux of transfer standard lamps	**0.46**

Measurement condition:
Temperature:(23±2)°C Humidity:(60±10)%rh

Table 20 Measurement Result of NMC-A*STAR

Lamp No.	**Current (A)**	**Initial**			**Return**		
		Voltage (V)	**Luminous flux(lm)**	**Distribution Temperature (K)**	**Voltage (V)**	**Luminous flux(lm)**	**Distribution Temperature (K)**
P507	1.9250	95.61	2489	2788	95.77	2491	2788
P536	1.9559	93.92	2492	2788	94.17	2496	2788
P554	1.9510	92.51	2425	2788	92.73	2430	2788

7. Analysis of measurement result

7.1 Measurement results between the participant and pilot laboratory

The transfer standards were measured twice in each participating laboratory except for NIML-SIRIM. The initial and returned measurement values show little difference. This means the artifacts were stable during the time span of the comparison. The transfer standards of NIM were measured twice at NIM, and once at NIML-SIRIM. The average of the initial and returned values is considered as the measurement result of the laboratory. The reported initial and returned measurement value are shown in Table 21. The average of the reported results, NIM's measurement results and the ratio Φ_{NMI}/Φ_{NIM} , mean of ratios of each participant to NIM, are shown in Table 22.

Table 21 Initial and returned measurement results of the participant

Acronym	Lamp No.	Initial Result			Returned Result		
		Voltage (V)	Luminous flux(lm) Φ_{NMI}	Distribution Temperature (K)	Voltage (V)	Luminous flux(lm) Φ_{NMI}	Distribution Temperature (K)
CMS	P560	86.070	2040	2761	86.217	2035	2770
	P563	88.030	2040	2747	88.130	2039	2785
	P587	89.134	1940	2725	89.219	1940	2748
NMISA	NSF2	91.60	2350	2734±40	91.60	2348	2734±40
	NSF4	91.89	2363	2733±40	91.89	2361	2733±40
	NSF5	89.73	2297	2733±40	89.73	2294	2733±40
	NSF6	92.50	2393	2742±40	92.50	2387	2742±40
KRISS	P567	88.31	2014	2753±23	88.32	2009	2753±23
	P569	90.37	2179	2753±23	90.38	2174	2750±23
	P570	91.42	2218	2753±23	91.48	2213	2749±23
NIMT	P572	94.506	2512	2788	94.574	2521	2788
	P573	95.082	2507	2788	95.107	2512	2788
	P574	95.328	2495	2788	95.378	2499	2788
NMIJ/AIST	P531	95.558	2544.5	2788	95.574	2544.3	2788
	P537	93.787	2502.2	2788	93.824	2505.1	2788
	P539	94.461	2520.1	2788	94.493	2525.3	2788
NML-SIRIM*	P561	91.874	2322.8	2788	91.925	2324.3	2788
	P562	92.325	2340.8	2788	92.367	2342.6	2788
	P564	89.622	2271.8	2788	89.681	2272.5	2788
NPLI	P591	95.15	2454	2766±20	95.15	2455	2785±20
	P592	95.28	2566	2780±20	95.35	2568	2800±20
	P593	95.05	2408	2779±20	95.05	2410	2784±20
NMC-A*STAR	P507	95.61	2489	2788	95.77	2491	2788
	P536	93.92	2492	2788	94.17	2496	2788
	P554	92.51	2425	2788	92.73	2430	2788

*It is the measurement result at NIM.

Table 22 Measurement results and ratios between the participant and pilot laboratory

Acronym	Lamp No.	Measurement results at the participant laboratory Φ NMI		Measurement results at the pilot laboratory Φ NIM		Ratio $m_{k,j}(=\Phi_{(k,j)\mathrm{NMI}}/\Phi_{(k,j)\mathrm{NIM}})$ $m_k=\frac{1}{n_k}\sum_{j=1}^{n_k}m_{k,j}$
		Luminous flux(lm) Φ_{NMI}	Distribution Temperature (K)	Luminous flux(lm) Φ_{NIM}	Distribution Temperature (K)	
CMS	P560	2037.5	2766	2028.8	2761	1.00429
	P563	2039.5	2766	2024.5	2753	1.00741
	P587	1940.0	2737	1932.5	2726	1.00390
					average	**1.00520**
NMISA	NSF2	2349.0	2734	2343.7	2796	1.00225
	NSF4	2362.0	2733	2359.0	2798	1.00127
	NSF5	2295.5	2733	2293.4	2794	1.00093
	NSF6	2390.0	2742	2385.0	2798	1.00210
					average	**1.00164**
KRISS	P567	2011.5	2753	2025.6	2753	0.99304
	P569	2176.5	2752	2192.9	2770	0.99252
	P570	2215.5	2751	2234.9	2775	0.99131
					average	**0.99229**
NIMT	P572	2516.5	2788	2500.7	2805	1.00630
	P573	2509.5	2788	2493.2	2804	1.00654
	P574	2497.0	2788	2481.4	2804	1.00629
					average	**1.00638**
NMIJ/AIST	P531	2544.4	2788	2532.7	2803	1.00463
	P537	2503.7	2788	2490.4	2806	1.00534
	P539	2522.7	2788	2509.9	2806	1.00511
					average	**1.00503**
NML-SIRIM	P561	2338		2323.6	2788	1.00620
	P562	2357		2341.7	2788	1.00653
	P564	2286		2272.2	2788	1.00607
					average	**1.00627**
NPLI	P591	2454.5	2776	2432.7	2787	1.00897
	P592	2567.0	2790	2551.7	2810	1.00599
	P593	2409.0	2782	2391.3	2781	1.00741
					average	**1.00746**
NMC-A*STAR	P507	2490.0	2788	2497.7	2804	0.99692
	P536	2494.0	2788	2500.3	2806	0.99749
	P554	2427.5	2788	2433.2	2802	0.99765
					average	**0.99735**

7.2 Measurement Uncertainties

The uncertainty of the participant result in this comparison should include the uncertainty in the participant laboratory and in the pilot laboratory. Components are defined as follows:

U*rel*(*unit*) The claimed uncertainty of the participant which includes the realization and maintenance of the luminous flux unit and transferring to the batch of transferred standards.

At the pilot laboratory, two source of uncertainty have to be regarded
U*rel*(*homog.*) The homogeneity of a batch of lamps used by a participant as transfer standards, the homogeneity is calculated individually for each participant using the following formula.

$$m_{k,j} = \frac{\Phi_{(k,j)\mathrm{NMI}}}{\Phi_{(k,j)\mathrm{NIM}}}$$

where *j* is the number of transfer standards of a participant, *k* is the number of the participant, $\Phi_{(k,j)\mathrm{NMI}}$ is the luminous flux measurement result in the participant laboratory, $\Phi_{(k,j)\mathrm{NIM}}$ is the luminous flux measurement result in the pilot laboratory, $m_{k,j}$ is the luminous flux value of the participant divided by the NIM-value, is the ratio of the jth lamp of the *k*th participant.

$$m_k = \frac{1}{n_k}\sum_{j=1}^{n_k} m_{k,j}$$

$$u_{rel}^2(\mathrm{hom}\,og.) = \frac{1}{(n_k - 1)\cdot n_k}\sum_{j=1}^{n_k}(m_{k,j} - m_k)^2$$

The batch ratio m_k is the mean of $m_{k,j}$ with a related relative uncertainty $u_{\mathrm{rel}}(\mathrm{hom}\,og.)$

U*rel*(*NIM*) The relative transfer uncertainty at the pilot laboratory, $U_{\mathrm{rel}}(\mathrm{NIM}) = 0.09$ %; see table 23.

Table 23 Transfer uncertainty in the pilot laboratory

Source of Uncertainty	Type	Relative standard uncertainty %
Correction of the stability of the measurement system	B	0.04
Lamp Current measurement	B	0.06
Repeatability of the measurement lamp	A	0.02
V(λ) mismatch	B	<0.05
Combined relative standard uncertainty %		**0.09**

The combined standard uncertainty of each participant in this comparison is:

$$u_{rel}^2(\text{batch}) = u_{rel}^2(\text{unit}) + u_{rel}^2(\text{hom}\,og) + u_{rel}^2(\text{NIM})$$

The uncertainties mentioned above are listed for each participant in table 24 and are also used in Fig.5 to draw uncertainty bars.

7.3 Agreements among laboratories

As all participant measurement results are compared with the pilot laboratory NIM. It is possible to use NIM's value as a reference to calculate the difference between any two participants and check whether they agree within the uncertainty, as show in table 24 and Fig. 5.

Table 24 Measurement uncertainty (k=1) and ratios of luminous flux between the participant and pilot laboratory

Acronym	$u_{\mathrm{rel},k}$ (unit) %	$u_{\mathrm{rel},k}$ (homog.) %	u_{rel}(NIM) %	$u_{\mathrm{rel},k}$ (batch) %	Ratio m_k
CMS	0.75	0.11	0.09	0.76	1.00520
NMISA	0.47	0.03	0.09	0.48	1.00164
KRISS	0.58	0.05	0.09	0.59	0.99229
NIM	0.24	0.04	0.09	0.26	1.00000
NIMT	0.52	0.01	0.09	0.53	1.00638
NMIJ/AIST	0.37	0.02	0.09	0.38	1.00503
NML-SIRIM	0.75	0.01	0.09	0.76	1.00627
NPLI	0.61	0.09	0.09	0.62	1.00746
NMC-A*STAR	0.46	0.02	0.09	0.47	0.99735

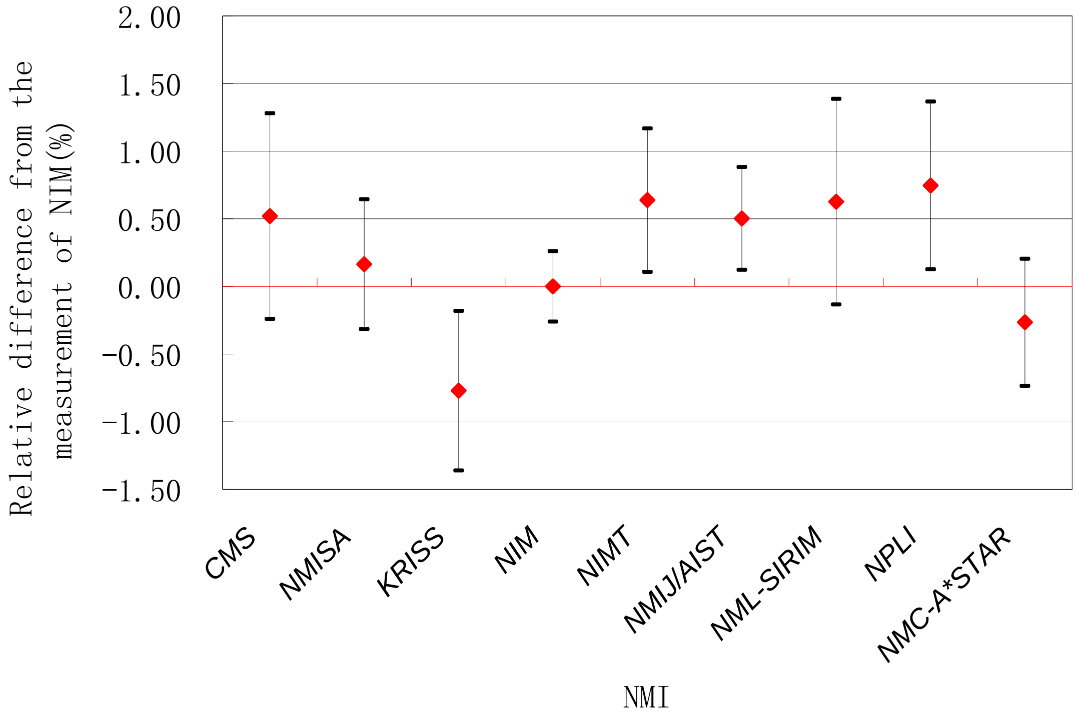

Figure 5 Relative difference and combined standard uncertainty (k=1) of luminous flux value against the reference value of NIM

8. Linking to the CCPR Key Comparison

8.1 Calculation of the comparison reference value

Linking of the APMP regional comparison to the CCPR K4 Key Comparison follows the method described by Elster, Link and Woger (2003). Three of the participating laboratories – NIM, NMISA and NMIJ/AIST participated in the CCPR luminous flux comparison. It is assumed that the link laboratory results in the CCPR comparison and RMO comparison are uncorrelated.
When calculating the key comparison reference value (KCRV) as a mean weighted by laboratory uncertainties, CCPR apply a lower-limit to uncertainty that is derived as the average of the uncertainty values of those participants whose reported uncertainties smaller than or equal to the median of all the participants; for CCPR K4 this value was 0.30 %. In calculating the linking value from this comparison, the uncertainty of the NIM result is raised from its measured value of 0.26 % to the cut-off value of 0.30 %. Table 25 shows the results from the APMP comparison to be used to link to the CCPR comparison.

Table 25 Performance of link laboratories in APMP comparison

Laboratory	**Ratio** m_k	**Standard uncertainty** $u_{\mathrm{rel},k}(\text{batch})$ %	**Weighting Parameter** w_k %
NIM	1.00000	0.26	0.30
NMISA	1.00164	0.48	0.48
NMIJ/AIST	1.00503	0.38	0.38

The weighted average $\bar{v}_{APMP}$ of the three laboratories is calculated using weighting parameter w_k.

$$\bar{v}_{\mathrm{APMP}} = \frac{1}{\sum_{k=1}^{3}\frac{1}{w_k^2}}\sum_{k=1}^{3}\frac{m_k}{w_k^2} = \frac{\frac{1.00000}{(0.30\%)^2}+\frac{1.00164}{(0.48\%)^2}+\frac{1.00503}{(0.38\%)^2}}{\frac{1}{(0.30\%)^2}+\frac{1}{(0.48\%)^2}+\frac{1}{(0.38\%)^2}} = 1.00187$$

The relative uncertainty of this value is given by

$$u_{\mathrm{rel}}^2\left(\bar{v}_{\mathrm{APMP}}\right) = \frac{1}{\sum_{k=1}^{3}\frac{1}{w_k^2}} = \frac{1}{\frac{1}{(0.30\%)^2}+\frac{1}{(0.48\%)^2}+\frac{1}{(0.38\%)^2}}$$

$$u_{\mathrm{rel}}\left(\bar{v}_{\mathrm{APMP}}\right) = 0.21\%$$

Values of NIM, NMISA and NMIJ/AIST obtained in the CCPR-K4 comparison, relative to the KCRV, are shown in Table 26. Uncertainties are combined standard uncertainties. Again to calculate the weighted average for these laboratories in the CCPR comparison, the weighting parameter for NIM is increased to the cut-off value of 0.30 %.

Table 26 Performance of link laboratories in the CCPR-K4 comparison

Laboratory	**Ratio** $v_k\ \left(=\Phi_{k,\mathrm{NMI}}/\Phi_{\mathrm{CCPR}}\right)$	**Standard uncertainty** $u_{\mathrm{rel},k}(\text{batch})$ %	**Weighting parameter** w_k %
NIM	0.9978	0.26	0.30
NMISA	0.9999	0.53	0.53
NMIJ/AIST	1.0017	0.34	0.34

The weighted average $\bar{v}_{CCPR}$ of the three laboratories at CCPR K4 is calculated using weighing parameter w_k.

$$\bar{\nu}_{\text{CCPR}} = \frac{1}{\sum_{k=1}^{3}\frac{1}{w_k^2}}\sum_{k=1}^{3}\frac{\nu_k}{w_k^2} = \frac{\frac{0.9978}{(0.30\%)^2}+\frac{0.9999}{(0.53\%)^2}+\frac{1.0017}{(0.34\%)^2}}{\frac{1}{(0.30\%)^2}+\frac{1}{(0.53\%)^2}+\frac{1}{(0.34\%)^2}} = 0.99957$$

The relative uncertainty of this value is given by

$$u_{\text{rel}}^2\left(\bar{\nu}_{\text{CCPR}}\right) = \frac{1}{\sum_{k=1}^{3}\frac{1}{w_k^2}} = \frac{1}{\frac{1}{(0.30\%)^2}+\frac{1}{(0.53\%)^2}+\frac{1}{(0.34\%)^2}}$$

$$u_{\text{rel}}\left(\bar{\nu}_{CCPR}\right) = 0.21\%$$

Hence the value measured by a laboratory in this comparison relative to the CCPR K4 key comparison reference value is found by multiplying the ratio m_k(Table 22) with uncertainty of $U_{\text{rel},k}$(batch) (Table 24) by $r = \bar{\nu}_{\text{CCPR}} / \bar{\nu}_{\text{APMP}}$ = 0.99957/1.00187 = 0.99770

with an uncertainty of $u_{\text{rel}}(r) = \sqrt{u_{\text{rel}}^2\left(\bar{\nu}_{\text{APMP}}\right) + u_{\text{rel}}^2\left(\bar{\nu}_{\text{CCPR}}\right)} = \sqrt{0.21^2 + 0.21^2}\,\% =$ 0.30%

The comparison result for each laboratory in this APMP comparison, even those providing the linking, can be related to the CCPR K4 reference value by multiplying the measured ratio m_k of Table 22 by r

For the laboratories in this comparison not present at the CCPR level, the result and its uncertainty are given by

$$\nu_{k,\text{KCRV}} = r m_k$$

$$u_{\text{rel}}^2\left(\nu_{k,\text{KCRV}}\right) = u_{\text{rel}}^2\left(r\right) + u_{\text{rel}}^2\left(m_k\right) = u_{\text{rel}}^2\left(r\right) + u_{\text{rel},k}^2\left(\text{batch}\right)$$

For the linking laboratories, the ratio r and the measured ratio m_k are correlated with a covariance given by $u\left(r, m_k\right) = -\bar{\nu}_{\text{CCPR}}\, u_{rel}^2\left(\bar{\nu}_{\text{APMP}}\right)$ and the relative uncertainty is given by

$$u^2_{\text{rel}}\left(\nu_{k,\text{KCRV}}\right) = u_{\text{rel}}^2\left(r\right) + u_{\text{rel},k}^2\left(\text{batch}\right) + 2\frac{u\left(r, m_k\right)}{r m_k}$$

The degrees of equivalence D_i given by $D_k = \nu_{k,\text{KCRV}} - 1$ are defined as the relative differences between the linked value from the APMP comparison and the KCRV of the CCPR comparison. CCPR treat the uncertainty of the KCRV as negligible.

8.2 Results

For each laboratory participating in this comparison, Table 27 shows the degree of equivalence (DOE) to the KCRV and its expanded uncertainty (k=2). The degrees of equivalence and their expanded uncertainties are plotted in Fig 6.

Table 27 Degrees of equivalence of APMP laboratories for measurements of luminous flux, relative to the CCPR K4 KCRV

Laboratory	D_k (%)	$U_{rel}(D_k)$ k=2 (%)
CMS	0.29	1.63
KRISS	-1.00	1.32
NIMT	0.41	1.22
NML-SIRIM	0.40	1.63
NPLI	0.51	1.37
NMC-A*STAR	-0.49	1.11
NIM	-0.23	0.52
NMISA	-0.07	0.96
NMIJ/AIST	0.27	0.76

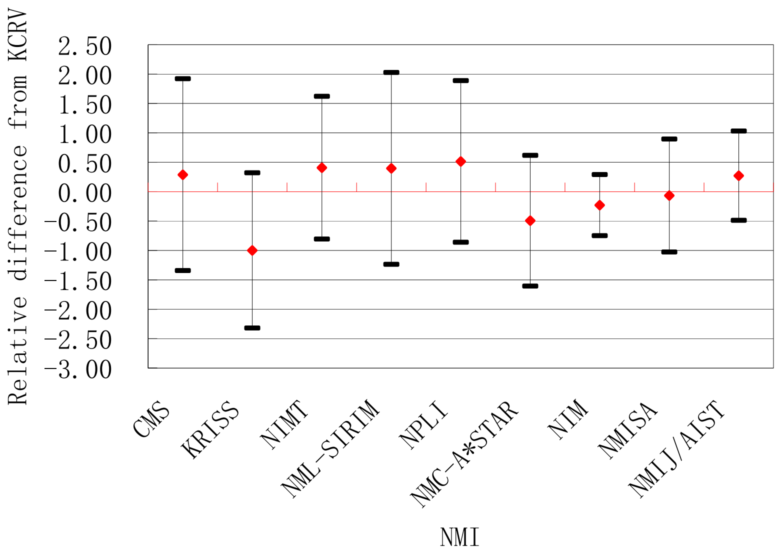

Figure 6 Degrees of equivalence of APMP laboratories for measurements of luminous flux, relative to the CCPR Key Comparison reference value KCRV 1997. Uncertainties are for k=2.

9.Discussion

For the three APMP laboratories linking this comparison to the CCPR comparison, the degrees of equivalence to the KCRV value are consistent between the APMP and CCPR level (Table 28).

Table 28 Degrees of equivalence of APMP link laboratories between the APMP and CCPR level

Laboratory	Ratio: ν_{KCRV} $\Phi_{Lab.}/\Phi_{KCRV}$	Ratio: ν_{APMP} $\Phi_{Lab.}/\Phi_{APMP}$	Difference between ν_{KCRV} and ν_{APMP}
NIM	0.9978	0.9981	0.0003
NMISA	0.9999	0.9998	-0.0001
NMIJ/AIST	1.0017	1.0032	0.0015

NIMT obtain their primary standard from NMIJ; the results in the APMP comparison are consistent for these two laboratories.

NMC-A*STAR derive their luminous flux standards from NPL; its DOE of (-0.49 ± 1.11) % overlaps that of NPL (from the CCPR level) of (0.37 ± 0.40) % at the k=2 level, but not at k=1 level.

CMS traces luminous flux to NIST. The CMS DoE of (0.29 ± 1.63) % is consistent with that of NIST of (-0.21 ±0.62) %, from the CCPR level.

NML-SIRIM traces its standards to KRISS. The results for the two laboratories are consistent at the k=2 level, although the difference in DOE is moderately large. These two laboratories do not use the LF200 lamp as their primary standard and the large uncertainties in this comparison may be related to the lamp type.

Reference

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