APMP Key Comparison
of
Luminous Intensity (APMP.PR-K3.a)

Final Report

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ABSTRACT

International key comparison on luminous intensity was organized by the Asia Pacific Metrology Programme (APMP), identified as APMP.PR-K3.a, and carried out with coordination by National Metrology Institute of Japan (NMIJ-AIST) as the pilot laboratory. In total, 13 national metrology institutes (NMIs) participated in the comparison. The linkage to the key comparison reference value (KCRV) of luminous intensity scale was provided through the result of the CCPR key comparison, CCPR-K3.a (1999), by NMIJ-AIST and National Institute of Metrology, China (NIM). In the comparison, a group of luminous intensity standard lamps were used as transfer standard lamps. The comparison was organized as star-type comparison (Participant - Pilot - Participant). Luminous intensity scale of each participant was compared with the KCRV through the measurement results of the transfer standard lamps and associated uncertainties, and the relationship with the KCRV were evaluated to declare its international equivalence. All the data analyses were performed in accordance with the CCPR guidelines.

This report provides the overview of the comparison, including measurement procedure, transfer standard lamps, data analysis, measurement results of all the participant NMIs and their uncertainties. The final result of the comparison is given as the degree of equivalence (DoE) of the participants obtained based on the difference from the KCRV determined in CCPR-K3.a (1999) and their stated uncertainties.

Revision History

2022.11.11	Draft A Ver.1
2023.4.4	Draft A Ver.2
2023.5.12	Draft A Ver.3
2023.6.12	Draft B Ver.1
2023.6.23	Draft B Ver.2
2023.11.24	Draft B Ver.3
2024.8.7	Final report

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1. Introduction

Under the Mutual Recognition Arrangement (CIPM MRA) signed in 1999, the metrological equivalence of national measurement standards has been determined by a set of key comparisons chosen and organized by the Consultative Committees of the Comité International des Poids et Mesures (CIPM) working closely with the Regional Metrology Organizations (RMOs). One of the key comparisons arranged by the Comité Consultative de Photométrie et Radiométrie (CCPR) is CCPR-K3.a (1999)*, which is the comparison on luminous intensity scale piloted by the PTB, conducted in 1997-1998 with 17 participants. The final report of the CCPR-K3.a (1999) was published in 1999 [1].

* To clearly identify the CCPR key comparison this report refers to for KCRV, the year of publication is added to the comparison identifier in this report.

In 2007, Technical Committee for Photometry and Radiometry (TCPR) in APMP proposed several regional key comparisons (APMP key comparisons) to link CCPR key comparisons. One of them was the comparison on luminous intensity, which was denoted as APMP.PR-K3.a. The objective of APMP key comparisons is to determine the Degrees of Equivalence (DoE) for NMIs, which didn't participate in the corresponded CCPR key comparison, with the link to the key comparison reference value (KCRV). The DoE states the relative difference of each participant's value from KCRV with the associated expanded uncertainty.

APMP.PR-K3.a was carried out according to the technical protocol and relevant guidelines to define the procedure to organize international comparisons. [2, 3, 4]. Technical protocol was prepared by the pilot laboratory and approved by all the participants on July 2012, and CCPR WG-KC in December 2012.

This report includes the information about the organization of the comparison (Section 2), procedure and timeline of the comparison (Sections 3), measurement conditions (Section 4), comparison measurement at the pilot laboratory (Section 5), measurement results (Section 6), determination of DoE with the link to CCPR-KCRV (Section 7) and the summary of the comparison (Section 8). It also includes some annexes that describe measurement reports submitted by each participant (Annex A), corrections and discussions made in the pre-draft A stage (Annex B), relative data distributed in the pre-draft A3 stage (Annex C), and the statement provided by a participant regarding their measurement results (Annex D).

2. Organization of the comparison

2.1 Participants

APMP.PR-K3.a has in total thirteen participants, which are listed in Table 1. It includes the information about the economies they belong to, the name of contact persons, contact details and their acronyms to be used hereinafter in this document. All the participating laboratories are National Metrological Institutes (NMIs).

NMIJ-AIST served as the pilot laboratory for this comparison. In the CCPR-K3.a (1999) comparison, four NMIs (CSIRO (formerly NMIA), NIM, NMISA (formerly CSIR) and NMIJ-AIST (formerly ETL)) were participated from the APMP region. Among them, NIM and NMIJ-AIST acted as link laboratories for this comparison, which provided their maintained luminous intensity scale to relate to KCRV of the CCPR-K3.a (1999) comparison to determine the DoE of each participant.

Note. Kazakhstan Institute of Metrology (RSE "KazInMetr") from Kazakhstan withdrew its participation after the protocol agreed and the comparison was launched.

Table 1 List of participant NMIs

Economy	Institute (Acronyms)	Contact Person	Contact Details
China	National Institute of Metrology (NIM)	Liu Hui	No.18, Bei San Huan Dong Lu, Chaoyang, Dist, Beijing, P.R.China, 100013 E-mail: liuhui@nim.ac.cn
Chinese Taipei	Center for Measurement Standards (CMS/ITRI)	Wen-Chun Liu	Bldg. 16, 321, Sec. 2, Kuang Fu Road, Hsinchu 30011, Chinese Taipei E-mail: liuwenchun@itri.org.tw
Hong Kong	Standards and Calibration Laboratory (SCL)	Brenda Lam	36/F, Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong E-mail: hslam@itc.gov.hk
Indonesia	National Standardization Agency of Indonesia (BSN)*	Dini Suryani	Kawasan Kompleks PUSPIPTEK, Puslit KIM-LIPI Gdg. 420 Setu, Tangerang Selatan, Banten, Indonesia, 15315 E-mail: dini@bsn.go.id
India	National Physical Laboratory (NPLI)	V. K. Jaiswal Parag Sharma	Dr. K.S. Krishnan Road, New Delhi - 110 012 E-mail: sharmap2@nplindia.org, sharmap2@nplindia.org
Japan (Pilot Lab)	National Metrology Institute of Japan	Hiroshi Shitomi	1-1-1 Umezono, Tsukuba, Ibaraki, JAPAN 3058563

	(NMIJ-AIST)		E-mail: h-shitomi@aist.go.jp
Malaysia	National Metrology Institute of Malaysia (NMIM) **	Mohd Nizam Abdullah	Lot Pt 4803, Bandar Baru Salak Tinggi 43900 Sepang Selangor Darul Ehsan, Malaysia E-mail: mnizam@sirim.my
New Zealand	Measurement Standards Laboratory (MSL)	Neil Swift	69 Gracefield Rd, PO Box 31 310 Lower Hutt 5040, New Zealand E-mail: neil.swift@measurement.govt.nz
Thailand	National Institute of Metrology (NIMT)	Rojana Leecharoen	3/4-5 Moo 3 Klong 5, Klong Luang Pathumthanee, 12120 Thailand E-mail: rojana@nimt.or.th
Singapore	National Metrology Centre (NMC-A*STAR)	Liu Yuanjie	8 CleanTech Loop, Unit 01-20, Singapore 637145, Singapore E-mail: liu_yuanjie@nmc.a-star.edu.sg
Vietnam	Vietnam Metrology Institute (VMI)	Cao Xuan Quan	8 Hoang Quoc Viet Road, Caugiay District, Hanoi, Vietnam E-mail: quancx@tbt.gov.vn
South Africa	National Metrology Institute of South Africa (NMISA)	Rheinhardt Sieberhagen	Building 5, CSIR Campus, Brummeria, Pretoria, 0184, South Africa E-mail: rsieberhagen@nmisa.org
Egypt	National Institute for Standards (NIS)	Mohamed Shafik	Tersa St. Elharam, Giza, Egypt P.O. Box 136 Giza Code 12211 E-mail: mohamedshafikkhalil@gmail.com

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** Formerly "National Metrology Laboratory (NML-SIRIM)"

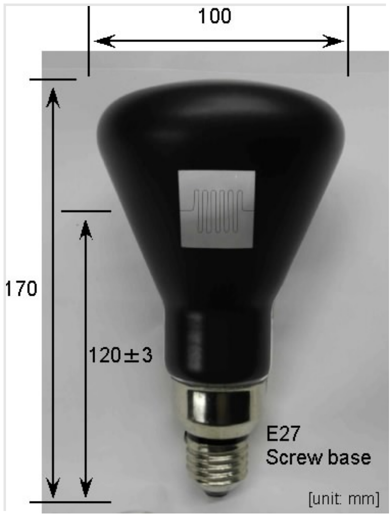
2.2 Form of comparisons

The comparison was carried out by means of the measurement of luminous intensity values of standard lamps calibrated by each participant. In this comparison, a group of standard lamps were prepared by each participant (or by pilot laboratory as loaned lamps in some cases) as transfer standard lamps, and each participant submitted them to the pilot laboratory with their calibrated values and associated uncertainties.

The link laboratories provided their maintained values of luminous intensity as the basis of the KCRV of CCPR-K3.a (1999) with their transfer standard lamps to the pilot laboratory. Based on the comparison result at the pilot laboratory for all the transfer standard lamps and the measurement results from the link laboratories, measurement results from non-link laboratories were connected to the KCRV and the DoE were obtained with the associated uncertainty.

2.3 Transfer standards

In the CCPR-K3.a (1999) comparison, two types of tungsten filament gas-filled incandescent lamps, Osram Wi41/G lamp and NPL/Polaron LIS lamp, were used as transfer standard lamps of luminous intensity. Considering the importance to have a better link to the KCRV by minimizing the comparison uncertainty in the pilot laboratory due to the difference of lamp types, it was decided to use a single type of standard lamp, the Osram Wi41/G lamps (Fig.1), as the transfer standard lamps.



(Front View) (Side View)

Fig. 1 Photo of a luminous intensity standard lamp (Osram Wi41/G)

Participants were recommended using its own set of transfer standard lamps that are selected by themselves. The recommended set of the transfer standards used for this comparison was a group of three lamps or more. Besides Osram Wi41/G type lamps with an E27 screw base as shown in Fig.1, some participants have another type of Wi41/G lamp with a lamp mount, base plate and an alignment tool as shown in Fig.2. For APMP.PR-K3.a comparison, the pilot laboratory accepted both type of Wi41/G lamps as transfer standard lamps.

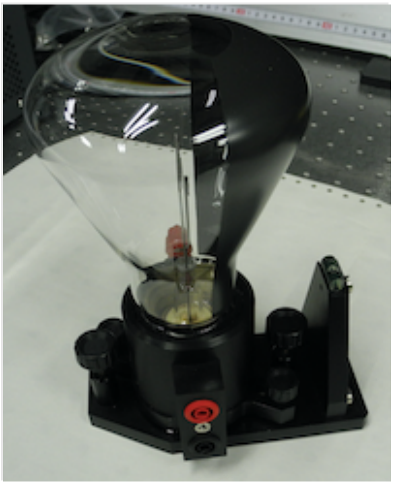


Fig. 2 Photo of another type of luminous intensity standard lamp
(OSRAM Wi41/G with a lamp mount, a base plate, and an alignment tool)

Furthermore, the pilot laboratory prepared in total six Wi41/G lamps as loaned lamps for participants that didn't have their own transfer standard lamps suitable for this comparison. These loaned lamps are divided into two groups, and NMIM and BSN used each of them.

2.4 Type of comparison

Because of the fragile nature of the incandescent lamps used for transfer standard lamps, it was decided that this comparison should be a star-type comparison. For the comparison, the measurement sequence "Participant – Pilot – Participant" was taken to achieve the comparison results. The transfer standard lamps were initially calibrated by a participant. Then they were sent to the pilot laboratory together with their individual operating conditions. After the calibration in the pilot laboratory, they were returned to the participant and the second calibration was made to monitor the lamp stability. In the case that a participant used the transfer standard lamps prepared by the pilot laboratory, they were initially transported from the pilot laboratory to the participant with the lamp operating condition specified by the pilot laboratory.

3. Comparison procedures and time schedule

3.1 Preparation of the technical protocol

The protocol was prepared by the pilot laboratory and approved by all the participants in July 2012. Then it was submitted to the CCPR WG-KC for their approval. After some minor corrections in response to the comments by the CCPR WG-KC, the protocol was finally approved by the CCPR WG-KC in December 2012.

3.2 Transportation and measurement of the transfer standard lamps

Participants were divided into five groups (Group 1 to 5) according to the time of period allotted for their measurements. Due to the limitation of operatable calibration numbers at the pilot laboratory in one period, each group had maximum of 4 participant NMIs. Each time slot had 8 weeks (2 months) for calibration and transportation of transfer standard lamps. Table 2 showed the summary of measurement and transportation history of APMP.PR-K3.a comparison together with the number of transfer standard lamps each participant used.

Table 2 Timetable for the comparison

NMI Acronym	Number of lamps	Transportation	Pilot laboratory		Report submitted to the pilot laboratory
			Receipt	Returned	
NIM	4	Air cargo	2013-08-15	2013-09-29	2014-01-30
CMS/ITRI	4	Air cargo	2013-09-30	2013-12-10	2014-06-17
SCL	3	Hand-carry	2013-10-02	2013-12-05	2014-02-11
BSN	3	Air cargo	2013-10-31	2014-02-17	2014-05-23
NPLI	3	Air cargo	2013-09-30	2013-11-06	2014-02-10
NMIJ-AIST	3	No travel	-	-	2015-09-09
NMIM	2*	Air cargo	2013-10-31	2014-02-17	2014-09-17
MSL	3	Air cargo	2013-11-05	2014-01-24	2014-06-30
NIMT	3	Hand-carry	2013-02-07	2013-04-04	2013-07-15
NMC-A*STAR	3	Air cargo	2013-08-19	2013-09-21	2014-01-29
VMI	3	Air cargo	2013-07-09	2013-09-12	2014-02-26
NMISA	3	Air cargo	2014-02-07	2014-04-04	2014-08-07
NIS	4	Air cargo	2013-04-05	2013-06-20	2014-05-24

* NMIM initially used three lamps provided by the pilot laboratory. During the measurement in the participant laboratory, one of them was accidentally broken. As a result, NMIM used only two transfer standard lamps for the comparison.

Including 3 lamps from the pilot laboratory that did not travel, the total number of lamps received at the pilot laboratory was 41 lamps. A list of the lamps received during the comparison is given in Table 2 together with the information about the way of transportation and the record the pilot laboratory received and shipped them. As for the transportation of the transfer standard lamps, it was highly recommended that they should be transported by hand-carrying from the participant to the pilot laboratory and back again to the participant. As an alternative way, shipping by air-cargo was accepted under the responsibility of the participants for any loss or damage during the transportation. As shown in Table 2, only two participant NMIs chose the hand-carry whereas all the others sent their transfer standard lamps between the participant and the pilot laboratory by air-cargo. During the comparison, no lamps were received broken at the pilot laboratory as well as at the participant NMIs when they were shipped by air-cargo.

3.3 Reporting the measurement results

According to the protocol, participants were requested to submit measurement data of their transfer standard lamps including the uncertainty within 6 weeks of the completion of their measurements. All the participants submitted their measurement results, together with the information about their measurement facilities, scale traceability, measurement procedures, environment conditions and uncertainty budget to the pilot laboratory by September 2014. The measurement reports submitted by the participants are shown in Annex A.

3.4 Pre-draft-A1: Verification of reported results

Pre-draft A process for an RMO key comparison consists of three stages according to the CCPR-G2 and CCPR-G6 [4, 5]. Pre-draft A1 process was started on 9 September 2015. The pilot laboratory assembled the data collected from each participant and individually sent to each participant their reported values for verification. During this stage, CMS/ITRI made data correction and BSN submitted revised uncertainty budget table. In addition, most participants made minor editorial corrections on the report. All the data received and used by the pilot laboratory were confirmed by each participant and the pre-draft A1 was closed on 1 October 2015. Detail of the discussion and corrections made during the pre-draft A1 stage is shown in Annex B.

3.5 Pre-draft-A2: Review of uncertainty budget tables

Pre-draft A2 process was started on 9 October 2015. The pilot laboratory distributed the uncertainty budgets of all the participants to all the participants for their review. Collected comments were assembled and forwarded anonymously to the participant being addressed, then replies from the participant involved were received and reported to all the participants by the pilot laboratory. During the pre-draft A2 process, CMS/ITRI modified the uncertainty budget table based on the comments received. Revised uncertainty budget was reviewed again and agreed by all the participants. Pre-draft A2 was closed on 26 July 2016 with a summary provided to the participants, which is attached in Annex B. Review comments and the reply from respective participants including the history of corrections are also shown in Annex B.

3.6 Pre-draft-A3: Review of relative data

The pilot laboratory prepared the "Relative Data" of each participant, which were calculated according to CCPR-G2 [5]. Relative data was prepared by removing the information about the difference of measurement values between each participant and the pilot laboratory from the final comparison result. The main objectives of the relative data review are to check the internal consistency of all the transfer standard lamps measured at each participant and their stability before and after the measurement of the pilot laboratory and subsequent transportation. The relative data for each participant presented in tabulated and graphic forms are shown in Annex C.

Relative data were distributed to the participants on 24 November 2018. No non-link participant requested to remove the data of a specific lamp because of inconsistency of relative data observed between their 1st and 2nd measurements or other reasons. The other actions taken during the pre-draft A stage based on the review of relative data are shown below.

NIM, one of the link laboratories, suggested to withdraw the measurement results for two lamps (Wi41/G-1 and Wi41/G-27) when the link to KCRV was provided to obtain the DoE. The main reason was the drift of these lamps observed in the relative data, which was attributed to the change of filament condition during the comparison (see Annex B.3). NIM argued that these changes might result in significant impacts and the above two lamps should be removed for better link to KCRV with smaller link uncertainty. NMISA requested to correct their reported values and uncertainty budget table based on the relative data. The report from NMISA with technical rationale is shown in Annex B.3. All the measurement data reported by the participants with the corrections during the pre-draft A stage are shown in Annex A. Pre-draft A3 was closed on 29 September 2022.

3.7 Draft-A

The first version of the draft A report was distributed on 10 November 2022. All the participants were asked to review it and send comments to the pilot laboratory, if any, by the end of 2022. During the review of the first version of the draft A report, CMS/ITRI reported that they found the problem of their measurement results in their follow-up analysis of the data, which would be probably due to malfunction of their instrument. They hoped to have the opportunity to explain the problem they might have had during the comparison. A supplementary report was prepared and added to this report as Annex D.

Further review was made two more time after the corrections based on the collected comments. No significant technical issues were raised during the review. The second and the third version of the draft A was distributed on 4 April 2023 and 8 May 2023, respectively. In addition to editorial corrections including grammatical improvements, some technical comments and questions from participants were addressed by the pilot laboratory. It was confirmed that the draft A report was approved by all the participants on 9 June 2023.

3.8 Draft-B

A draft B report was prepared by addressing editorial comments collected during the review of the third version of draft A. It was submitted to TCPR chair on 12 June 2023. After review by the TCPR chair, the second version of draft B, which included some minor editorial corrections, was submitted to CCPR WG-KC for approval. Based on the WG-KC comments provided on 17 October 2023, the third version of the draft B was re-submitted to WG-KC on 24 November 2023. Draft B report was approved by CCPR WG-KC on 24 July 2024, followed by the final review by CCPR in August 2024.

4. Measurement Conditions

4.1 Measurand and basic measurement parameters

As is shown in 2.3, Osram Wi41/G lamps were used as the transfer standard lamps for this comparison. The measurand for the comparison was the luminous intensity of a lamp under the defined DC current which acted as the setting parameter. Each lamp was operated at the specified operating condition, which was defined by each participant to achieve the designated distribution temperature (DT) or correlated color temperature (CCT). The recommended DT or CCT was 2800 K ± 20 K. In the comparison, higher temperature condition up to 2856 K (with maximum possible allowance of 20 K) was accepted, if a participant used such operating condition in their scale realization or routine calibration. In either case, the participants were requested to report DT (or CCT) values used for their measurement. The measurement distance, defined from the center of the lamp filament to the reference plane of a photometer to be used along with the optical axis, was not specified in the protocol, but it was recommended to use a sufficiently large photometric distance. The participants were asked to report the distance value used for their measurement. In this comparison, eight participants applied CCT, and the other five labs applied DT as the parameter. The spectral responsivity of the photometer used for the comparison measurement at the pilot laboratory was a good match to the photopic luminous efficiency function $V(\lambda)$ (See 5.2), which made the error due to the difference of CCTs and DTs for participants' lamps negligible.

4.2 Operation of transfer standard lamps

During the comparison, the transfer standard lamps were measured in the base-down position. The luminous intensity of the lamps was measured together with the values of lamp current and voltage. It was recommended to measure the lamp voltage at the vicinity of the lamp base using the four-pole technique with stabilization control of the specified lamp current. The lamp polarity for the DC operation was specified by each participant. The pilot laboratory used the same lamp polarity as specified by the participants for the measurement of their lamps.

4.3 Traceability

In the comparison, traceability of the calibration to the international system of units (SI) for the measurement instruments was required. Traceability of luminous intensity standard maintained by each participant is divided into three categories; 1) traceable to its own primary realization of the candela, 2) traceable to another NMI that has the primary realization, and 3) traceable to SI via calibration by an accredited laboratory, respectively. Among the participants of this comparison, five NMIs have the luminous intensity scale by their own primary realization, whereas seven NMIs have secondary traceability, and one NMI belongs to category 3.

4.4 Other conditions

Standard laboratory conditions during the calibration were 23 °C ± 2 °C for ambient temperature and 50 % ± 20 % for relative humidity. No participant reported the measurement under other conditions. Participants were asked to measure the luminous intensity of their transfer standard lamps independently at least twice, with re-alignment and turning on/off, in one measurement round. In the comparison, their mean or final declared value of the set was required and used in the analysis of the data. Considering the nature of the incandescent-based standard lamps, that their intensity would change depending on the total burning time, it was recommended to record the total burning time of the transfer standard lamps for correction, if applicable.

4.5 Measurement instructions

In the measurement of luminous intensity, the origin of the optical axis was defined at the center of the filament of the lamp. The optical axis for the measurement was defined as the direction normal to the filament plane that consisted of the horizontal axis and the lamp axis as shown in Fig.3.

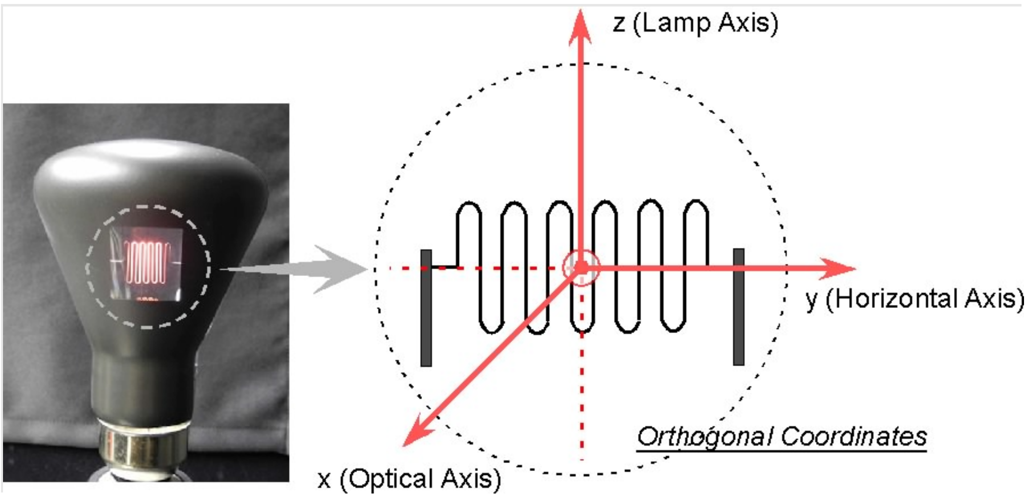


Fig. 3 Lamp geometry and coordinates

The Wi41/G-type lamp has a black mask on the anterior half of the lamp bulb to block the radiation from other than the filament. For the luminous intensity measurement using this type of lamp, care should be taken to measure the radiation only going through the opening of the mask. One example is placing an additional aperture screen in front of the lamp to block the radiation from the perimeter of the lamp bulb where no mask is placed. A preliminary study by the pilot laboratory revealed that the apparent luminous intensity would increase by an order of 0.1 % if there is no additional aperture screen to limit the FOV within the opening of the mask.

4.6 Measurement uncertainty

Participants were required to submit uncertainty budget tables that listed all the uncertainty contributions in the luminous intensity measurement with specific values to show the magnitude of the contribution and the number of degrees of freedom. The measurement uncertainty was estimated according to the ISO Guide to the Expression of Uncertainty in Measurements [6].

The following are the major uncertainty contributions in luminous intensity calibration, shown in the protocol as examples, which were recommended for consideration.

- Uncertainty associated with the reference standard used for the calibration

- Uncertainty associated with random noise during transfer measurement
- Uncertainty associated with lamp alignment
- Uncertainty associated with photometric distance
- Uncertainty associated with spectral mismatch of the photometer to $V(\lambda)$
- Uncertainty associated with non-linearity of the photometer
- Uncertainty associated with stray light
- Uncertainty associated with environmental effects such as the change of temperature and/or humidity
- Uncertainty associated with the error in electrical parameters
- Uncertainty associated with the drift (or ageing) of the lamp
- Uncertainty associated with the instability of whole calibration facilities
- other additional contributions specific to measurement facilities at each participant

5. Outline of the comparison measurement at the pilot laboratory

5.1 Reference standard lamps for the comparison measurement

Luminous intensity values of all the transfer standard lamps submitted by participants were compared with those of two reference standard lamps maintained by the pilot laboratory. During the comparison measurement at the pilot laboratory, two coil-M-type luminous intensity standard lamps (55 V-330 W, Toshiba) were used as the reference standard lamps. They are the same type of lamps as those being used to maintain the luminous intensity scale at the pilot laboratory. Basic specifications of the reference standard lamps are shown in Table 3. All the transfer standard lamps from the participants were compared with the reference standard lamps on the photometric bench according to the procedure shown in 5.2.

Table 3　Outline of the reference standard lamps used for the comparison measurement

Lamp ID	Lamp voltage (V)	Typical lamp current (A)	Initial luminous intensity (cd)
DSC6403	55.45	5.836	603.26
DSC6407	54.26	5.831	575.36

The total lamp burning time for each reference standard lamp during the comparison was around 15 hours. Their long-term stability was monitored by periodically comparing the lamps' output signal with another set of luminous intensity standard lamps with less total burning time. The lamp stability check was made at the beginning of the comparison, and when the total lamp burning time became 6 hours and 12 hours. Fig. 4 shows the result of the lamp stability check. Fig. 4 clearly indicates that the reference standard lamps used in this comparison showed superior stability whose change rate with respect to the lamp burning time is less than 0.02 %/h at the maximum and in most cases less than 0.005 %/h. The observed ageing of the reference standard lamps was considered as a correction factor when the luminous intensity value of each transfer standard lamp was compared according to the accumulated lamp burning time at the time of the measurement.

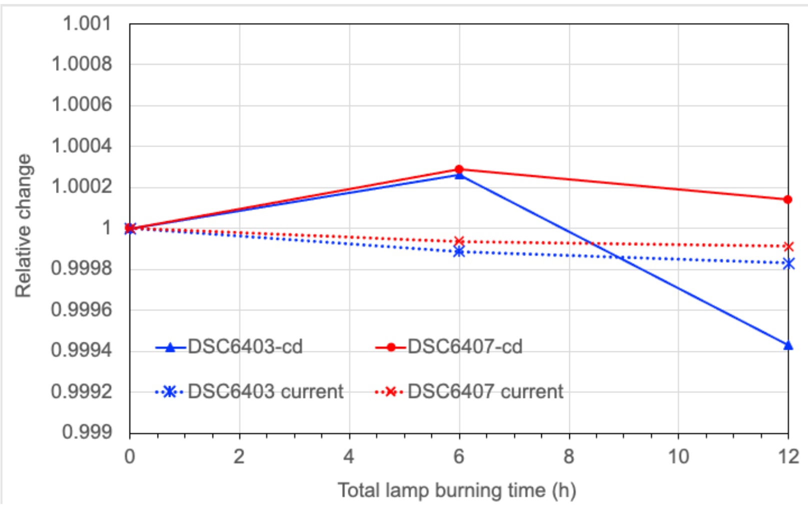


Fig.4　Ageing properties of reference standard lamps used in the comparison

5.2 Comparison measurement at the pilot laboratory

Principle for the comparison measurement was strict substitution between participants' lamps and the reference standard lamps under the same photometric distance. All the comparison measurements were made at the photometric distance of 2.7 m. A photometer used for the comparison measurement has approximated spectral response to $V(\lambda)$, whose general $V(\lambda)$ mismatch index, f_1' value is around 2.1 %. Distribution temperature (or color temperature) of each transfer standard lamp was checked in terms of the blue(B)/red(R) ratio using two detectors whose spectral responsivity curves peak around 460 nm and 660 nm, respectively. For the comparison measurement at the pilot laboratory, a spectral mismatch correction was not applied as the estimated spectral mismatch error was negligibly small, less than 0.01 %, considering the expected temperature difference among the lamps to be measured and good $V(\lambda)$ approximation of the photometer. All the tranfer standard lamps were operated in DC mode with PC-controlled stabilization at the specified lamp current. The lamp current was measured via a calibrated standard shunt resistor of 100 mΩ. The lamp voltage was measured at the vicinity of the lamp base using four-pole technique. For the transfer standard lamps, the pilot laboratory applied the same lamp operating condition including the lamp polarity as specified by each participant. For further detail of the procedure for the comparison measurement, including the outline of the comparison facilities, see Annex A.6. The reference standard lamps used at the pilot laboratory was operated under constant-voltage mode with a specified lamp voltage as a setting parameter.

The luminous intensity measurements of transfer standard lamps at the pilot laboratory were repeated on three different days. The reference standard lamps and the transfer standard lamps were measured twice in a day, which were designed to be in a time-symmetrical sequence to reduce the drift of the photometer. As a result, each lamp had six measurement data points whose average was used as the measurement result at the pilot laboratory.

The relative transfer uncertainty at the pilot laboratory used for the purpose of relatively comparing the luminous intensity values of transfer standard lamps is shown in Table 4. It corresponds to the extract of uncertainty factors except for the ones relevant to the luminous intensity scale, from the full uncertainty budget table shown in Annex A.6. Reproducibility of transfer standard lamps in the measurement at the pilot laboratory are included into the lamp inhomogeneity effect shown in 6.2.

Table 4 Relative transfer uncertainty at the pilot laboratory

	Uncertainty component	Relative standard uncertainty (%)
1	Lamp current measurement	0.01
2	Photometric distance	0.02
3	Lamp alignment	0.06
4	Lamp output fluctuations	0.02
Relative combined standard uncertainty		0.07

5.3 Selection and characterization of the loaned transfer standard lamps

In the initial preparation stage of the comparison, the pilot laboratory selected the transfer standard lamps used as loaned lamps. In total, 14 luminous intensity standard lamps (Wi41/G) owned by the pilot laboratory were benchmarked in terms of their stability. Fig. 5 shows changes in luminous intensity, B/R ratio and lamp current for all the test lamps after 15 hours of burning. For this benchmarking survey, the test lamps were operated at a specific lamp voltage with a constant-voltage control. All the data were taken on the same measurement setup as described in 5.2. The observed change in luminous intensity for 15 hours of burning varied from 0.09 % to 0.49 %. 9 lamps out of 14 showed stability of 0.3 % or less, that would correspond to a potential change of less than 0.02 % for 1 hour operation. Considering the stability properties shown in Fig.5 as well as other inspection properties such as the condition of the lamp bulb or filament shape, 6 lamps were selected as the loaned transfer standard lamps.

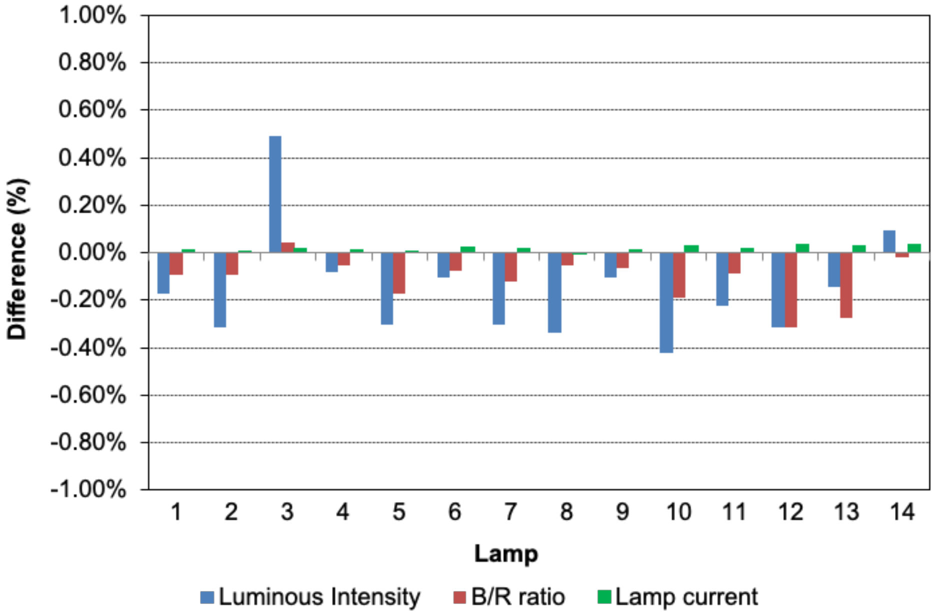


Fig.5 Result of performance check at the pilot laboratory with 15 hours of burning

6. Measurement results

6.1 Measurement results for each participant

In this comparison, a batch of the transfer standards were measured before and after their transportation. The average of these two measurements was taken as the final measurement value to be compared by the pilot laboratory. Measurement results of the lamps by each participant and the pilot laboratory are shown from Table 5 to Table 17.

In these tables, U_α and I_α denote measured lamp voltage in V, and luminous intensity in cd of each transfer standard lamp for the participant "α", respectively. $u(I_\alpha)$ represents relative standard uncertainty reported by each participant expressed to 2 significant digits.

Table 5 Comparison of measurement results between NIM and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{NIM} / V	I_{NIM} / cd	$u(I_{NIM})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{NIM} / I_{pilot})
Wi41/G-1	1	30.41	272.5	0.21	30.385	275.09	0.9928
	2	30.41	273.7	0.21			
Wi41/G-22	1	30.38	273.7	0.21	30.362	275.21	0.9947
	2	30.38	273.8	0.21			
Wi41/G-27	1	30.26	273.6	0.21	30.234	274.07	0.9967
	2	30.25	272.7	0.21			
Wi41/G-189	1	29.73	269.4	0.21	29.714	270.83	0.9951
	2	29.73	269.6	0.21			
						Average	**0.9949**

Note: As stated in 3.6, NIM suggested to withdraw the measurement results for Wi41/G-1 and Wi41/G-27 in the calculation of the DoE as a link laboratory. Average value shown in the bottom-most line of Table 5 is calculated using the data of Wi41/G-22 and Wi41/G-189 only.

Table 6 Comparison of measurement results between CMS and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{CMS} / V	I_{CMS} / cd	$u(I_{CMS})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{CMS} / I_{pilot})
CMS 1	1	30.699	275.7	0.35	30.699	271.54	1.0159
	2	30.727	276.0	0.35			
CMS 2	1	30.187	272.0	0.35	30.180	266.24	1.0218
	2	30.184	272.1	0.35			
CMS 3	1	29.917	276.4	0.35	29.914	271.82	1.0159
	2	29.921	275.9	0.35			
CMS 4	1	30.360	283.1	0.35	30.355	278.66	1.0177
	2	30.357	284.1	0.35			
						Average	**1.0178**

Table 7 Comparison of measurement results between SCL and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{SCL} / V	I_{SCL} / cd	$u(I_{SCL})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{SCL} / I_{pilot})
130117-1	1	30.42621	281.09	0.62	30.419	282.54	0.9933
	2	30.42404	280.18	0.62			
130117-3	1	30.54368	277.78	0.61	30.535	279.10	0.9940
	2	30.54112	277.04	0.61			
130117-4	1	30.53750	281.10	0.61	30.528	282.38	0.9940
	2	30.53324	280.25	0.61			
						Average	**0.9937**

Table 8 Comparison of measurement results between BSN and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{BSN} / V	I_{BSN} / cd	$u(I_{BSN})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{BSN} / I_{pilot})
73	1	30.216	269.7	0.47	30.415	275.58	0.9772
	2	30.222	268.9	0.46			
91	1	30.083	265.1	0.47	30.283	271.59	0.9748
	2	30.088	264.4	0.46			
96	1	29.988	263.0	0.47	30.180	267.82	0.9803
	2	29.993	262.1	0.46			
						Average	**0.9774**

Table 9 Comparison of measurement results between NPLI and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{NPLI} / V	I_{NPLI} / cd	$u(I_{NPLI})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{NPLI} / I_{pilot})
OSRAM Wi41/G: 60	1	30.42	280.8	0.36	30.414	282.20	0.9943
	2	30.42	280.4	0.36			
OSRAM Wi41/G: 67	1	30.36	276.3	0.36	30.356	278.36	0.9932
	2	30.36	276.6	0.36			
OSRAM Wi41/G: 87	1	30.41	276.6	0.36	30.404	279.27	0.9899
	2	30.41	276.3	0.36			
						Average	**0.9925**

Table 10 Comparison of measurement results between NMIJ and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{NMIJ} / V	I_{NMIJ} / cd	$u(I_{NMIJ})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{NMIJ} / I_{pilot})
#2	1	29.515	244.53	0.29	29.515	244.53	1.0000
	2	29.512	244.53	0.29			
#70	1	29.651	246.00	0.29	29.651	246.00	0.9998
	2	29.650	245.90	0.29			
#85	1	29.401	246.36	0.29	29.401	246.36	1.0002
	2	29.401	246.45	0.29			
						Average	**1.0000**

Table 11 Comparison of measurement results between NMIM and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{NMIM} / V	I_{NMIM} / cd	$u(I_{NMIM})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{NMIIM} / I_{pilot})
77	1	31.760	299.57	0.45	31.359	302.94	0.9894
	2	31.774	299.92	0.45			
90	1	31.701	301.07	0.45	31.267	303.27	0.9931
	2	31.708	301.28	0.45			
						Average	**0.9913**

Table 12 Comparison of measurement results between MSL and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{MSL} / V	I_{MSL} / cd	$u(I_{MSL})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{MSL} / I_{pilot})
121220-1	1	30.4583	287.31	0.16	30.448	288.56	0.9954
	2	30.4575	287.13	0.16			
121220-2	1	30.3307	278.50	0.16	30.326	279.05	0.9983
	2	30.3314	278.67	0.16			
121220-3	1	30.2687	276.48	0.16	30.262	276.67	0.9995
	2	30.2695	276.59	0.16			
						Average	**0.9977**

Table 13 Comparison of measurement results between NIMT and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{NIIMT} / V	I_{NIMT} / cd	$u(I_{NIMT})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{NIMT} / I_{pilot})
0006	1	30.88	287.34	0.37	30.821	286.26	1.0035
	2	30.96	287.18	0.37			
0009	1	30.90	282.17	0.37	30.844	280.95	1.0060
	2	30.99	283.11	0.37			
0013	1	30.90	277.63	0.37	30.829	276.97	1.0044
	2	30.9	278.73	0.37			
						Average	**1.0046**

Table 14 Comparison of measurement results between NMC-A*STAR and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{A*STAR} / V	I_{A*STAR} / cd	$u(I_{A*STAR})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{A*STAR} / I_{pilot})
981232-868	1	30.174	277.0	0.28	30.159	276.93	0.9988
	2	30.101	276.2	0.28			
981232-984	1	30.044	265.4	0.28	30.045	266.65	0.9966
	2	30.042	266.1	0.28			
981232-988	1	30.033	273.2	0.28	30.017	273.86	0.9976
	2	30.031	273.2	0.28			
						Average	**0.9977**

Table 15 Comparison of measurement results between VMI and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{VMI} / V	I_{VMI} / cd	$u(I_{VMI})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{VMI} / I_{pilot})
0030	1	31.08	289.2	0.41	31.147	288.89	1.0007
	2	31.02	289.0	0.41			
0031	1	30.82	290.1	0.41	30.882	288.48	1.0053
	2	30.80	289.9	0.41			
0037	1	30.99	280.2	0.41	31.052	280.81	0.9982
	2	30.95	280.4	0.41			
						Average	**1.0014**

Table 16 Comparison of measurement results between NMISA and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{NMISA} / V	I_{NMISA} / cd	$u(I_{\mathrm{NMISA}})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{NMISA} / I_{pilot})
"24" 4595	1	30.258	269.7	0.73	30.244	273.88	0.9855
PTB 09	2	30.242	270.1	0.73			
"39" 4596	1	30.828	284.9	0.73	30.824	288.18	0.9888
PTB 09	2	30.816	285.0	0.73			
"42" 4597	1	30.727	277.4	0.73	30.721	281.37	0.9829
PTB 09	2	30.713	275.7	0.73			
						Average	**0.9857**

Table 17 Comparison of measurement results between NIS and the pilot laboratory

Lamp ID	Participant				Pilot		Batch ratio
	Round	U_{NIS} / V	I_{NIS} / cd	$u(I_{\mathrm{NIS}})$ / %	U_{pilot} / V	I_{pilot} / cd	(I_{NIS} / I_{pilot})
E13	1	32.11	290.3	0.61	32.285	300.32	0.9638
	2	32.07	288.6	0.61			
E14	1	32.08	280.9	0.61	32.078	280.95	1.0004
	2	32.03	281.2	0.61			
E15	1	32.33	281.7	0.61	32.440	281.16	1.0003
	2	32.26	280.8	0.61			
E17	1	31.64	278.2	0.61	31.715	283.35	0.9795
	2	31.61	276.9	0.61			
						Average	**0.9860**

6.2 Summary of the measurement results

Relative difference of measurement results between each participant and the pilot laboratory that is expressed as "(I_α / I_{pilot})-1" is shown in Table 18 and Fig.6. The error bars in Fig.6 represents the expanded uncertainty reported by each participant with the coverage factor of k = 2. In addition, inhomogeneity effect of the transfer standard lamps, which is used to determine DoE, is calculated individually for each batch of a participant in the same manner as the CCPR-K3.a (1999) [1] as follows,

$$u_{\alpha,\mathrm{homog}}{}^2 = \frac{1}{n_\alpha(n_\alpha - 1)} \sum_{j=1}^{n_\alpha} (v_{\alpha,j} - v_\alpha)^2$$
$$v_\alpha = \frac{1}{n_\alpha} \sum_{j=1}^{n_\alpha} v_{\alpha,j} \qquad (1)$$

where n_α is the number of lamps a participant α used for the comparison, $v_{\alpha,j}$ is the ratio of luminous intensity values between the participant (taken as average of the first and the second round) and the pilot laboratory for j-th lamps. The values of $u_{\alpha,\mathrm{homog}}$ for each participant are also shown in Table 18.

Data on the relative difference from the pilot laboratory shown in Table 18 are used to determine DoE, whose detail is described in chapter 7.

Table 18 Summary of the measurement results

NMI Acronym α	Relative difference (I_α / I_{pilot})-1	Reported relative standard uncertainty $u(I_\alpha)$	Inhomogeneity effect of the transfer standard lamps $u_{\alpha,homog}$
NIM	-5.12×10^{-3}	2.1×10^{-3}	2.0×10^{-4}
CMS/ITRI	1.78×10^{-2}	3.5×10^{-3}	1.4×10^{-3}
SCL	-6.28×10^{-3}	6.1×10^{-3}	2.3×10^{-4}
BSN	-2.26×10^{-2}	4.6×10^{-3}	1.6×10^{-3}
NPLI	-7.54×10^{-3}	3.6×10^{-3}	1.3×10^{-3}
NMIJ-AIST	-1.02×10^{-5}	2.9×10^{-3}	1.1×10^{-4}
NMIM	-8.73×10^{-3}	4.5×10^{-3}	1.8×10^{-3}
MSL	-2.27×10^{-3}	1.6×10^{-3}	1.2×10^{-3}
NIMT	4.63×10^{-3}	3.7×10^{-3}	7.4×10^{-4}
NMC-A*STAR	-2.33×10^{-3}	2.8×10^{-3}	6.4×10^{-4}
VMI	1.39×10^{-3}	4.1×10^{-3}	2.1×10^{-3}
NMISA	-1.43×10^{-2}	7.3×10^{-3}	1.7×10^{-3}
NIS	-1.40×10^{-2}	6.1×10^{-3}	8.9×10^{-3}

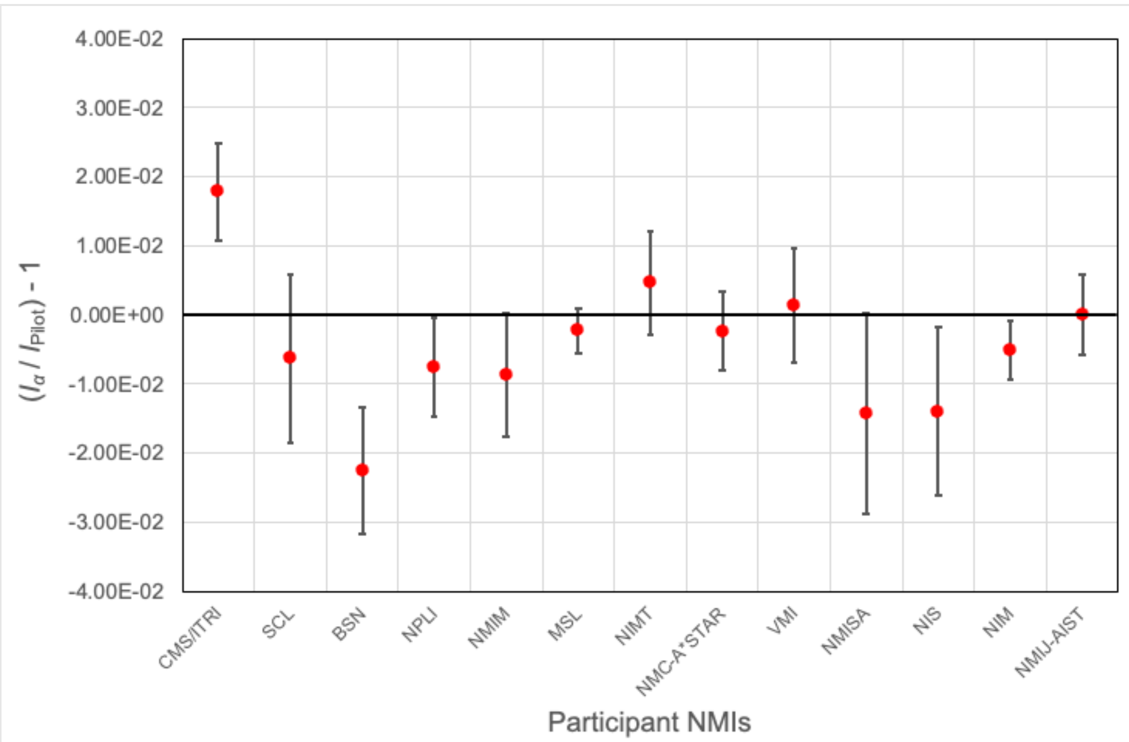


Fig.6 Relative difference of measurement results between each participant and the pilot laboratory, with error bars that represents relative expanded uncertainty (k = 2) reported by each participant

7. Linking to the CCPR-K3.a (1999)

7.1 General

Linking the result of APMP.PR-K3.a to the corresponding CCPR key comparison (CCPR-K3.a (1999)) follows the method defined in CCPR-G6 [4]. The aim of the analysis shown in this chapter is to evaluate the Degree of Equivalence (DoE) of the measurement result of non-link laboratories. DoE describes the discrepancy of a non-link laboratory scale from the KCRV determined at the CCPR-K3.a (1999) comparison. Among the participants of the CCPR-K3.a (1999), NMIJ-AIST and NIM acted as link laboratories this time.

7.2 Principle to calculate DoE

Unilateral DoE of the APMP PR-K3.a was determined according to the recommended analysis approach described in Appendix A of CCPR-G6. Among three cases shown in CCPR-G6, all the link laboratories are categorized into the case A2.3 "For the link of non-link laboratories when the pilot laboratory is a link laboratory". The DoE of a non-link laboratory, through the pilot and another link laboratory is given by:

$$D_{\alpha(p)} = D_p + \left(\frac{y_\alpha}{y_p} - 1\right)$$
$$D_{\alpha(l)} = D_l + \left(\frac{y'_p}{y'_l} - 1\right) + \left(\frac{y_\alpha}{y_p} - 1\right) \tag{2}$$

where $D_{\alpha(p)}$ and $D_{\alpha(l)}$ are the unilateral DoEs for the participant α calculated via the pilot laboratory p, and that calculated via the link laboratory l with the pilot laboratory p, D_p and D_l are the unilateral DoEs for the link laboratories p and l calculated during the corresponding KC, y_α/y_p is the average ratio (from multiple artifacts) of the measurement results between the participant and the pilot laboratory, and y'_p/y'_l is that between the pilot and the link laboratory, respectively. The participant α's DoE, D_α was calculated using weights W_p and W_l, as follows.

$$D_\alpha = W_p D_{\alpha(p)} + W_l D_{\alpha(l)}$$
$$W_p + W_l = 1 \tag{3}$$

The weights used in eq. (3) were obtained according to the following formulae.

$$W_p = \frac{\bar{W}}{\bar{\sigma}_p{}^2 - u_{p,\mathrm{r,RMO}}{}^2 - S_{RMO}{}^2}$$
$$W_l = \frac{\bar{W}}{\bar{\sigma}_l{}^2 + u_{p,\mathrm{r,RMO}}{}^2}$$
$$\bar{W} = \frac{\left(\bar{\sigma}_l{}^2 + u_{p,\mathrm{r,RMO}}{}^2\right)\left(\bar{\sigma}_p{}^2 - u_{p,\mathrm{r,RMO}}{}^2 - S_{RMO}{}^2\right)}{\bar{\sigma}_p{}^2 + \bar{\sigma}_l{}^2 - S_{RMO}{}^2} \tag{4}$$
$$\bar{\sigma}_p{}^2 = S_{\mathrm{KC}}{}^2 + S_{\mathrm{RMO}}{}^2 + u_{p,\mathrm{st}}{}^2 + u_{p,\mathrm{r,KC}}{}^2 + u_{p,\mathrm{r,RMO}}{}^2$$
$$\bar{\sigma}_l{}^2 = S_{\mathrm{KC}}{}^2 + S_{\mathrm{RMO}}{}^2 + u_{l,\mathrm{st}}{}^2 + u_{l,\mathrm{r,KC}}{}^2 + u_{l,\mathrm{r,RMO}}{}^2$$

In eq. (4), S_{KC} represents the transfer uncertainty of the CCPR-K3.a (1999), which may relate to an artifact instability factor calculated from known effects, or derived as additional factor applied during a Mandel-Paule approach in obtaining consistency of the KC results. As there is no specific value known for the typical artifact instability factor, nor did CCPR-K3.a (1999) use the Mandel-Paule approach, S_{KC} can be regarded as zero (S_{KC} = 0). S_{RMO} is the standard transfer uncertainty of the APMP.PR-K3.a, which may come from known artifact instability effect, or from the similar term during the corresponded CCPR key comparison. In the same manner as S_{KC}, S_{RMO} is also considered to be zero (S_{RMO} = 0) in this comparison. $u_{p,\mathrm{st}}$ and $u_{l,\mathrm{st}}$ are the standard uncertainties associated with reproducibility of the pilot and the link laboratory's scales between the KC and the RMO-KC. These factors are treated with other factors $u_{p,\mathrm{r,KC}}$ and $u_{l,\mathrm{r,KC}}$, which are the standard uncertainties associated with uncorrelated (random) effects of the pilot and the link laboratory during the CCPR-K3.a (1999). As the repot of CCPR-K3.a (1999) doesn't provide specific information on the uncorrelated uncertainties, the following approximation was applied here according to the CCPR-G6:

$$
\begin{aligned}
{u_{p,\mathrm{st}}}^2 + {u_{p,\mathrm{r,KC}}}^2 &= {u_p}^2 \\
{u_{l,\mathrm{st}}}^2 + {u_{l,\mathrm{r,KC}}}^2 &= {u_l}^2
\end{aligned}
\qquad (5)
$$

where u_p and u_l are the declared total standard uncertainty (both systematic and random effects) of the pilot and the link laboratory at the CCPR-K3.a (1999). $u_{p,\mathrm{r,RMO}}$ and $u_{l,\mathrm{r,RMO}}$ are the standard uncertainties associated with uncorrelated (random) effects at the pilot and the link laboratory for this comparison, respectively.

Based on the above-mentioned consideration, the weights shown in eq. (4) can be rewritten as follows.

$$
\begin{aligned}
W_p &= \frac{\bar{W}}{{\bar{\sigma}_p}^2 - {u_{p,\mathrm{r,RMO}}}^2} \\
W_l &= \frac{\bar{W}}{{\bar{\sigma}_l}^2 + {u_{p,\mathrm{r,RMO}}}^2} \\
\bar{W} &= \frac{\left({\bar{\sigma}_l}^2 + {u_{p,\mathrm{r,RMO}}}^2\right)\left({\bar{\sigma}_p}^2 - {u_{p,\mathrm{r,RMO}}}^2\right)}{{\bar{\sigma}_p}^2 + {\bar{\sigma}_l}^2} \\
{\bar{\sigma}_p}^2 &\approx {u_p}^2 + {u_{p,\mathrm{r,RMO}}}^2 \\
{\bar{\sigma}_l}^2 &\approx {u_l}^2 + {u_{l,\mathrm{r,RMO}}}^2
\end{aligned}
\qquad (6)
$$

The standard uncertainty of the DoE for the participant α; $u(D_\alpha)$ is obtained from the following formula.

$$
\begin{aligned}
u^2(D_\alpha) = {u_\alpha}^2 + {u_{\alpha,\mathrm{homog}}}^2 + \left({W_p}^2 - 2W_p\, w_p + {W_\mathrm{l}}^2 - 2W_l\, w_l\right){S_{\mathrm{KC}}}^2 + \\
u(x_{\mathrm{ref}})^2 + {W_p}^2\left({u_{p,\mathrm{st}}}^2 + {u_{p,\mathrm{r,KC}}}^2 + {u_{p,\mathrm{r,RMO}}}^2\right) + {W_l}^2\left({u_{l,\mathrm{st}}}^2 + {u_{l,\mathrm{r,KC}}}^2 + \right. \\
\left. {u_{l,\mathrm{r,RMO}}}^2\right) + \left({W_l}^2 + 1\right){S_{\mathrm{RMO}}}^2 + 2W_l\, {u_{p,\mathrm{r,RMO}}}^2
\end{aligned}
\qquad (7)
$$

where u_α represents the declared standard uncertainty of a participant α, $u_{\alpha,\mathrm{homog}}$ is the standard uncertainty due to inhomogeneity of a batch of lamps of the participant, $u(x_{\mathrm{ref}})$ is the standard uncertainty associated with the KCRV, and w_p and w_l are weights for the two link laboratories (including the pilot laboratory) in the calculation of the KCRV, respectively. Using the same simplification, eq. (6) can be rewritten as follows to be the final form to obtain $u(D_\alpha)$.

$$
\begin{aligned}
u^2(D_\alpha) = {u_\alpha}^2 + {u_{\alpha,\mathrm{homog}}}^2 + u(x_{\mathrm{ref}})^2 + {W_p}^2\left({u_p}^2 + {u_{p,\mathrm{r,RMO}}}^2\right) + \\
{W_l}^2\left({u_l}^2 + {u_{l,\mathrm{r,RMO}}}^2\right) + 2W_l\, {u_{p,\mathrm{r,RMO}}}^2
\end{aligned}
\qquad (8)
$$

What each term represents is as follows. The first term is the uncertainty from the participant, the second one is the effect of inhomogeneity of the transfer standard lamps of the participant, the third one is the effect by the linked KC, the fourth and the fifth ones are the effect coming from each link laboratory and the last term is the RMO effect, respectively.

Finally, the uncertainty of the unilateral DoE $U(D_\alpha)$ is given as an expanded uncertainty with the coverage factor of two ($k = 2$).

$$U(D_\alpha) = 2u(D_\alpha) \quad (9)$$

7.3 Determination of DoE

From the final report of CCPR-K3.a (1999) [1], the unilateral DoEs of the link laboratories (for this comparison, p = NMIJ and l = NIM) are $D_{\mathrm{NMIJ}} = -9.0 \times 10^{-4}$ and $D_{\mathrm{NIM}} = -1.6 \times 10^{-3}$, respectively.

As explained in 7.2, the transfer uncertainty of the CCPR-K3.a (1999), S_{KC} and the standard transfer uncertainty of the APMP.PR-K3.a, S_{RMO} are both regarded as zero ($S_{\mathrm{KC}} = 0$ and $S_{\mathrm{RMO}} = 0$). At the CCPR-K3.a (1999), the declared total standard uncertainty (both systematic and random effects) of the pilot laboratory (NMIJ) which acted also as a link laboratory is $u_{\mathrm{NMIJ}} = 2.8 \times 10^{-3}$, and that of another link laboratory (NIM) is $u_{\mathrm{NIM}} = 2.5 \times 10^{-3}$, respectively. As for the standard uncertainties associated with uncorrelated (random) effects on this comparison, the value for NMIJ calculated from its reported uncertainty budget is $u_{\mathrm{NMIJ,r,RMO}} = 7.0 \times 10^{-4}$, and that for NIM is $u_{\mathrm{NIM,r,RMO}} = 5.0 \times 10^{-4}$, respectively.

Note: When the KCRV of CCPR-K3.a (1999) was determined as a weighted mean by uncertainties of each participant, CCPR applied a cut-off value which was determined as the average of the uncertainty values of those participants that reported uncertainties smaller than or equal to the median of all the participants. The applied cut-off value for the CCPR-K3.a (1999) was 0.25 %, and the relative uncertainty NIM declared at that time was increased from its original value of 0.24 % to the cut-off value of 0.25 %.

By using the values shown above and eq. (5), the weights of two link laboratories are calculated to be $\boldsymbol{W_{\mathrm{NMIJ}} = 0.4713}$ and $\boldsymbol{W_{\mathrm{NIM}} = 0.5287}$, respectively.

Table 19 shows $D_{\alpha(p)}$ and $D_{\alpha(l)}$ values for non-link participants calculated according to eq. (2).

Table 19 Calculated $D_{\alpha(p)}$ and $D_{\alpha(l)}$ values

NMI Acronym α	$D_{\alpha(p)}$ (Unilateral DoEs for non-link participants calculated via NMIJ)	$D_{\alpha(l)}$ (Unilateral DoEs for non-link participants calculated via NIM with NMIJ)
CMS/ITRI	1.69×10^{-2}	2.14×10^{-2}
SCL	-7.18×10^{-3}	-2.73×10^{-3}
BSN	-2.35×10^{-2}	-1.90×10^{-2}
NPLI	-8.44×10^{-3}	-3.99×10^{-3}
NMIM	-9.63×10^{-3}	-5.18×10^{-3}
MSL	-3.17×10^{-3}	1.28×10^{-3}
NIMT	3.73×10^{-3}	8.17×10^{-3}
NMC-A*STAR	-3.23×10^{-3}	1.22×10^{-3}
VMI	4.91×10^{-4}	4.94×10^{-3}
NMISA	-1.52×10^{-2}	-1.07×10^{-2}
NIS	-1.49×10^{-2}	-1.05×10^{-2}

By using the values shown in Table 19 and the weights ($W_{\text{NMIJ}} = 0.4713$ and $W_{\text{NIM}} = 0.5287$) and other parameters mentioned above, the unilateral DoE of non-link participants and its associated uncertainty are obtained as shown in Table 20 and Fig. 7.

Table 20 Summary of the unilateral DoE, D_α, and the expanded uncertainty in the DoE, $U(D_\alpha)$ of all non-link participants

NMI Acronym α	D_α	$U(D_\alpha)$
CMS/ITRI	1.93×10^{-2}	8.6×10^{-3}
SCL	-4.83×10^{-3}	1.3×10^{-2}
BSN	-2.11×10^{-2}	1.1×10^{-2}
NPLI	-6.09×10^{-3}	8.8×10^{-3}
NMIM	-7.28×10^{-3}	1.1×10^{-2}
MSL	-8.16×10^{-4}	5.9×10^{-3}
NIMT	6.08×10^{-3}	8.7×10^{-3}
NMC-A*STAR	-8.78×10^{-4}	7.1×10^{-3}
VMI	2.84×10^{-3}	1.0×10^{-2}
NMISA	-1.28×10^{-2}	1.6×10^{-2}
NIS	-1.25×10^{-2}	2.2×10^{-2}

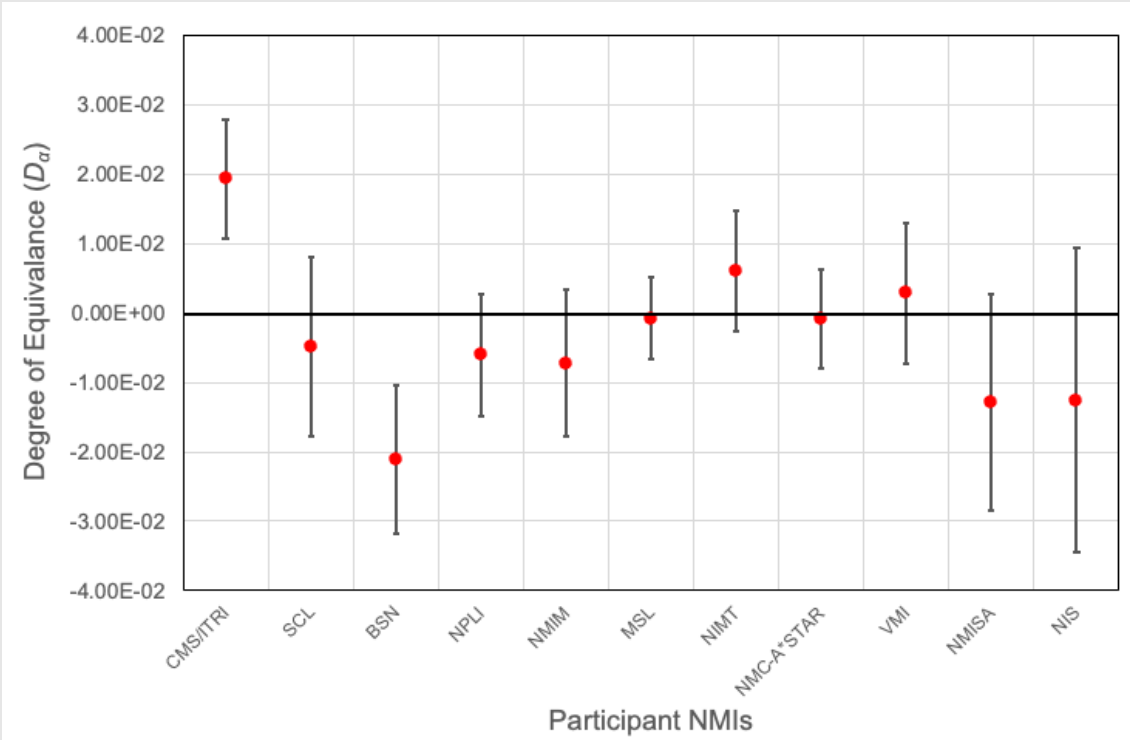


Fig.7 DoE to KCRV and its expanded uncertainty for APMP.PR-K3.a

7.4 Consistency of link laboratories

In this comparison, NIM and NMIJ provided the link to the CCPR-K3.a (1999). Unilateral DoEs of NIM and NMIJ at the CCPR-K3.a (1999) are $D_{\mathrm{NMIJ}} = -9.0 \times 10^{-4}$ and $D_{\mathrm{NIM}} = -1.6 \times 10^{-3}$, respectively. Difference of luminous intensity scale Δ_D with respect to KCRV for NIM and NMIJ at the CCPR-K3.a (1999) is calculated as follows.

$$\Delta_D = D_{\mathrm{NIM}} - D_{\mathrm{NMIJ}} = -7.0 \times 10^{-4} \tag{10}$$

The ratio of measured luminous intensity values of these two laboratories based on the comparison using two lamps (Wi41/G-22 and Wi41/G-189) during APMP.PR-K3.a is ($I_{\mathrm{NIM}} / I_{\mathrm{NMIJ}} = 0.9949$) as shown in Table 5. By using this value, difference between link laboratories Δ_{Link} observed in both comparisons (CCPR-K3.a (1999) and APMP.PR-K3.a) is calculated as follows.

$$\Delta_{\mathrm{Link}} = \Delta_D - \left(\frac{I_{\mathrm{NIM}}}{I_{\mathrm{NMIJ}}} - 1\right) = 4.4 \times 10^{-3} \tag{11}$$

Δ_{Link} can be considered as consistent if it is within its uncertainty. The uncertainty $u(\Delta_{\mathrm{Link}})$ should include components associated with random effects, stability of the scales, and stability of the artefacts considered in both comparisons as shown below.

$$u^2(\Delta_{\mathrm{Link}}) = u^2{}_{\mathrm{NIM,stab}} + u^2{}_{\mathrm{NIM,r,KC}} + u^2{}_{\mathrm{NIM,r,RMO}} + u^2{}_{\mathrm{NIM,homog}} + u^2{}_{\mathrm{NMIJ,stab}} + u^2{}_{\mathrm{NMIJ,r,KC}} + u^2{}_{\mathrm{NMIJ,r,RMO}} + u^2{}_{\mathrm{NIM,homog}} \quad (12)$$

where $u_{\mathrm{NIM,stab}}$ and $u_{\mathrm{NMIJ,stab}}$ represent the stability of the luminous intensity scale at NIM and NMIJ between the period from CCPR-K3.a (1999) to APMP.PR-K3.a, $u_{\mathrm{NIM,r,KC}}$ and $u_{\mathrm{NMIJ,r,KC}}$ are random uncertainties during CCPR-K3.a (1999), $u_{\mathrm{NIM,r,RMO}}$ and $u_{\mathrm{NMIJ,r,RMO}}$ are random uncertainties during APMP.PR-K3.a, and $u_{\mathrm{NIM,homog}}$ and $u_{\mathrm{NMIJ,homog}}$ are the instability effect of a batch of lamps used in the comparison measurement for APMP.PR-K3.a. As for the uncertainty associated with the stability, common transfer stability for a specific comparison should be ideally identified. However, as there is no common value that represents transfer stability for APMP.PR-K3.a, inhomogeneity effect for the batch of lamps shown in Table 18 is applied to this calculation. Considering the fact that around 15 years passed since the CCPR-K3.a (1999) when the comparison measurement was carried out for APMP.PR-K3.a, the stability of the luminous intensity scale would be expressed using systematic uncertainties for both laboratories as a conservative approximation. Under this approximation, eq. (12) can be reformed as follows.

$$u^2(\Delta_{\mathrm{Link}}) = u^2{}_{\mathrm{NIM,KC}} + u^2{}_{\mathrm{NIM,r,RMO}} + u^2{}_{\mathrm{NIM,homog}} + u^2{}_{\mathrm{NMIJ,KC}} + u^2{}_{\mathrm{NMIJ,r,RMO}} + u^2{}_{\mathrm{NIM,homog}} \quad (13)$$

where u_{NIM} and u_{NMIJ} represent the uncertainty declared in CCPR-K3.a (1999). By applying the values shown in 7.3 ($u_{\mathrm{NIM,KC}} = 2.4 \times 10^{-3}$, $u_{\mathrm{NIM,r,RMO}} = 5.0 \times 10^{-4}$, $u_{\mathrm{NIM,homog}} = 2.0 \times 10^{-4}$, $u_{\mathrm{NMIJ,KC}} = 2.8 \times 10^{-3}$, $u_{\mathrm{NMIJ,r,RMO}} = 7.0 \times 10^{-4}$, and $u_{\mathrm{NMIJ,homog}} = 1.1 \times 10^{-4}$), $u(\Delta_{\mathrm{Link}})$ is calculated to be $u(\Delta_{\mathrm{Link}}) = 3.8 \times 10^{-3}$, and its expanded uncertainty with the coverage factor of $k = 2$ is $U(\Delta_{\mathrm{Link}}) = 7.6 \times 10^{-3}$.

As $\Delta_{\mathrm{Link}} = 4.4 \times 10^{-3}$ is within its expanded uncertainty $U(\Delta_{\mathrm{Link}}) = 7.6 \times 10^{-3}$, it is concluded that the measurement results provided as link laboratories were consistent.

8. Summary

The metrological equivalence of luminous intensity standards was determined through a series of comparison of luminous intensity values transferred from 13 NMIs with a group of luminous intensity standard lamps. The comparison results were composed of the data on luminous intensity measurements taken at the pilot laboratory and the participant NMIs for in total 41 transfer standard lamps. They were linked to the KCRV of CCPR-K3.a (1999), via two link laboratories; NMIJ-AIST and NIM, then expressed in terms of unilateral DoE of each participant NMI.

The DoE confirmed in the comparison are almost within ±2 % level from the KCRV as a whole. While most of the non-link participants proved international equivalence of their luminous intensity standards by showing that the unilateral DoE of each participant was consistent within the uncertainty ($k = 2$) of the DoE, there were some cases that may need additional consideration on the possibility to underestimate the claimed uncertainty. For link laboratories, consistency between their maintained link to the KCRV for luminous intensity scale was confirmed.

Finally, the pilot laboratory (NMIJ-AIST) would like to thank all the participants for their kind support and cooperation during the comparison, which lead to the successful conclusion of the comparison. Special thanks go to NIM for their kind collaboration as a link-laboratory. The pilot laboratory is also indebted to Mr. Ichiro Saito, formerly NMIJ-AIST, for his dedicated help for the comparison measurement.

9. References

[1] CCPR Key Comparison K3a of Luminous Intensity and K4 of Luminous Flux with Lamps as Transfer Standards; PTB-Opt-62 (1999).

[2] CIPM MRA-G-11, Measurement comparisons in the CIPM MRA: Guidelines for organizing, participating and reporting (2021).
*Formerly, CIPM MRA-D-05; Measurement comparisons in the context of the CIPM MRA

[3] APMP–G2; The APMP Guidelines on conducting comparisons (2003).

[4] CCPR-G6, Guidelines for RMO PR Key Comparisons (2014).

[5] CCPR-G2, Guidelines for CCPR Key Comparison Report Preparation (2019).

[6] ISO/IEC Guide 98-3:2008; Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM)

Annex A: Measurement reports submitted by participant NMIs

A.1. National Institute of Metrology (NIM)

A.1.1 Measurement results

1) 1st Round (*July 2013*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
Wi41/G-1	5.8593	30.41	2860	272.5
Wi41/G-22	5.8489	30.38	2860	273.7
Wi41/G-27	5.8447	30.26	2858	273.6
Wi41/G-189	5.7797	29.73	2842	269.4

2) 2nd Round (*January 2014*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
Wi41/G-1	5.8593	30.41	2859	273.7
Wi41/G-22	5.8489	30.38	2860	273.8
Wi41/G-27	5.8447	30.25	2853	272.7
Wi41/G-189	5.7797	29.73	2839	269.6

Note: In the pre-draft A3 process, NIM showed their intention to withdraw the measurement result for two lamps (Wi41/G-1 and Wi41/G-27) from the calculation of the DoE as a link laboratory due to the concern for their drift.

A.1.2 Record of lamp operating time

1) Lamp No. Wi41/G-1

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13.07.19	5.8593	30.41	1200	Measurement Day-1
13.07.22		30.41	600	Measurement Day-2
13.08.05		30.41	1200	Measurement Day-3
14.01.17		30.41	1200	Measurement Day-4
14.01.26		30.41	1200	Measurement Day-5
14.01.27		30.41	600	Measurement Day-6

2) Lamp No. Wi41/G-22

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13.07.19	5.8489	30.38	1200	Measurement Day-1
13.07.22		30.38	600	Measurement Day-2

13.08.05		30.38	1200	Measurement Day-3
14.01.17		30.38	1200	Measurement Day-4
14.01.26		30.38	1200	Measurement Day-5
14.01.27		30.38	600	Measurement Day-6

3) Lamp No. Wi41/G-27

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13.07.19	5.8447	30.26	1200	Measurement Day-1
13.07.22		30.26	600	Measurement Day-2
13.08.05		30.26	1200	Measurement Day-3
14.01.17		30.25	1200	Measurement Day-4
14.01.26		30.25	1200	Measurement Day-5
14.01.27		30.25	600	Measurement Day-6

4) Lamp No. Wi41/G-189

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13.07.19	5.7797	29.73	1200	Measurement Day-1
13.07.22		29.73	600	Measurement Day-2
13.08.05		29.73	1200	Measurement Day-3
14.01.17		29.73	1200	Measurement Day-4
14.01.26		29.73	1200	Measurement Day-5
14.01.27		29.73	600	Measurement Day-6

A.1.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

The measurement is conducted with LMT full filter photometer detector, without diffuser, the diameter of the detector is about 9 mm, the f_1’ is 1.2 %. Picometer 6485 made by Keithley was used for the measurement of photo-current.

2) Laboratory reference standards used:

BDQ7 (Fig.A1.1) luminous intensity lamp, secondary primary standard, traced to latest candela realization, with current about 3.0000 A, 97 V, 420 cd, 2856 K were used as the reference standard. This lamp is made by Shanghai Yaming lighting factory, China.

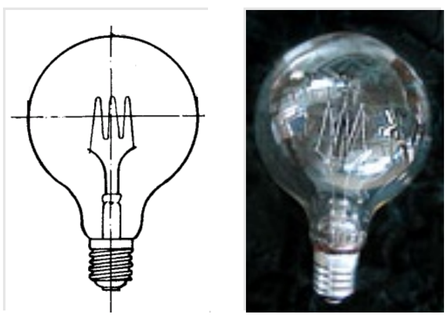


Fig. A1.1 BDQ7 Luminous intensity lamp

3) Description of measuring technique and procedure:

The measurement is conducted on an 8m photometer bench using a group of BDQ7 luminous intensity lamps as reference to calibrate a group of four Wi41/G lamps. At the initial measurement five BDQ7 type lamps were used, at the return measurement seven BDQ7 type lamps were used. The distance from the lamp to the detector is about 2.7 m. Four diaphragms are used to reduce the stray light (Fig. A1.2).

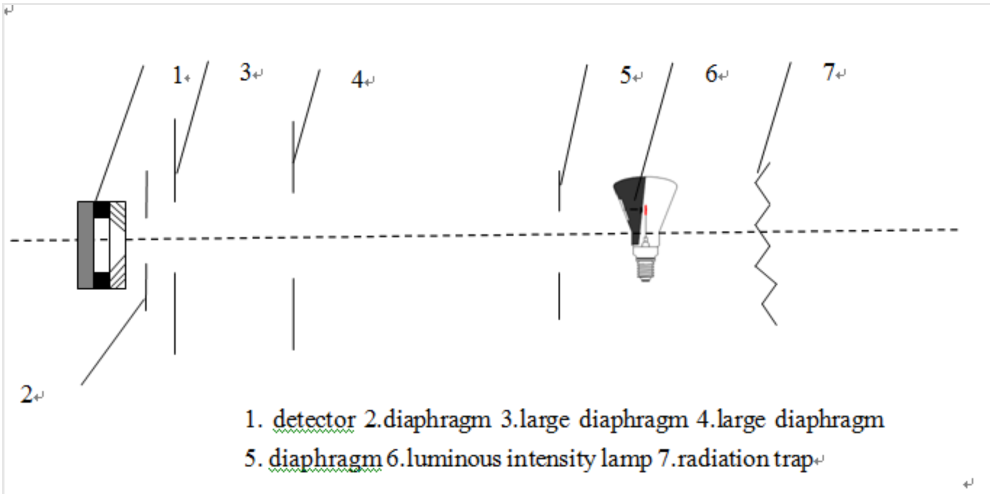


Fig. A1.2 Schematic diagram of the apparatus for luminous intensity lamp measurement

The Wi41/G lamps are calibrated at two independent rounds. At each round of the measurement all the lamps are re-aligned. The final result is the average of the two rounds.

The LMT photometer-detector with an input aperture diameter of approximately 9 mm was used to get the photo-current, which was measured by the 6485 picoammeter. In Fig. 2 diaphragm (2) is a small aperture with an rectangular opening of 50 mm × 50 mm, (3) (4) are larger diaphragm with rectangular opening of 80 mm × 80 mm and 150 mm × 150 mm, small diaphragm (5) located 200 mm before the lamp with a 60 mm diameter circular opening A black velvet cloth (7) was mounted 2.5 m behind the lamp, reflection of radiation by it is negligible.

4) Establishment or traceability route of primary scale:

The candela was realized last time at NIM in 2013, using the room temperature electrically calibrated radiometers. A group of BDQ8 and BDQ7 gas filled tungsten filament lamps, specially developed as secondary primary standards for luminous intensity, were calibrated by the radiometer, and the luminous intensity scale is maintained by them.

5) Description of calibration laboratory conditions:

At the 1st round measurement the ambient temperature was about 23 °C and the humidity was about 61 %RH. At the second-round measurement the ambient temperature was about 24 °C and the humidity was about 42 %RH. During the measurement, the temperature fluctuation is within 1 °C.

6) Operating conditions of the lamps:

The lamps were operated with DC power and fixed polarity, the center of the lamp is positive (+), and the side base is negative (-). The lamp voltage was ramped up in about 1 minute to the specific current of the lamp. The warm-up time is 10 minutes.

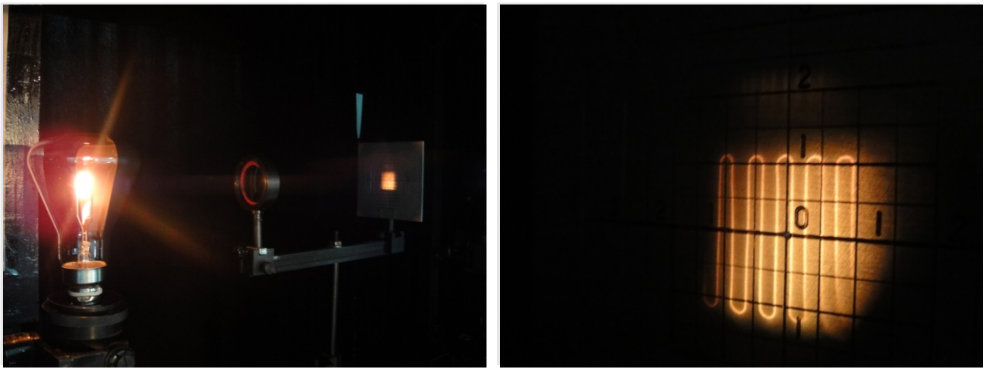


Fig. A1.3 Filament center regulator

A special carriage having five degrees of freedom in its physical adjustments was used for lamp position adjustment. A filament plane regulator (Fig.A1.3) is developed for the filament plane center positioning. Filament plane regulator is an optical image system which consists of indicator board and lens, the optical axis of it consistent with the optical axis of the photometric bench. The lamp was adjusted until the filament center coincides with the crosshairs in the indicator board, so that the optical axis of the photometric bench passes through the center of lamp filament plane.

The perpendicular position of the lamp was adjusted by the shadow of the filament. A parallel light beam is used to project the filament on an indicator board with a mark of line which vertical to the optical axis (plumb line). The lamp was adjusted until the width of the shadow of the filament is minimized and parallel to the line on the indicator.

A.1.4 Uncertainty budget of Measurement

Table A1.1 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Luminous intensity of reference standard	B	1000	0.16
2	Electrical supply	B	1000	0.05
3	Alignment of the detector and lamp, distance measurement	B	13	0.04
4	Repeatability of lamp	A	8	0.02
5	Drift of the lamp	B	15	0.11

6	Non-linearity	B	22	0.02
7	Spectral mismatch	B	13	0.01
8	Stray light	B	50	0.02
	Relative combined standard uncertainty		174	0.21
	Relative expanded uncertainty (with coverage factor (*k*) giving approximately 95 % confidence interval)			0.42

Note: During measurement the calibration facility is stable, no system change has been found.

A.2. Center for Measurement Standards (CMS/ITRI)

A.2.1 Measurement results

1) 1st Round (*Month, Year*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
CMS 1	5.8438	30.699	2813	275.7
CMS 2	5.8821	30.187	2811	272.0
CMS 3	5.8015	29.917	2821	276.4
CMS 4	5.8652	30.360	2820	283.1

2) 2nd Round (*Month, Year*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
CMS 1	5.8438	30.727	2839	276.0
CMS 2	5.8820	30.184	2821	272.1
CMS 3	5.8015	29.921	2840	275.9
CMS 4	5.8651	30.357	2833	284.1

A.2.2 Record of lamp operating time

1) Lamp No. CMS 1

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
				Measurement
2013.08.20	5.8437	30.702	2940	Day-1 (1)
2013.08.22	5.8438	30.704	2940	Day-2 (1)
2013.08.26	5.8439	30.699	2940	Day-3 (1)
2013.08.27	5.8438	30.698	2940	Day-4 (1)
2013.08.28	5.8438	30.700	2940	Day-5 (1)
2013.09.02	5.8438	30.700	2940	Day-6 (1)
2013.09.03	5.8436	30.699	2940	Day-7 (1)
2013.09.03	5.8438	30.699	2940	Day-7 (1)
2014.05.22	5.8437	30.730	2940	Day-1 (2)
2014.05.23	5.8437	30.727	2940	Day-2 (2)
2014.05.26	5.8437	30.730	2940	Day-3 (2)
2014.06.11	5.8437	30.727	2940	Day-4 (2)
2014.06.16	5.8438	30.731	2940	Day-5 (2)

2) Lamp No. CMS 2

Date	Current (A)	Voltage (V)	Operating time (s)	Activity

				Measurement
2013.08.20	5.8820	30.210	2940	Day-1 (1)
2013.08.22	5.8821	30.209	2940	Day-2 (1)
2013.08.23	5.8819	30.206	2940	Day-3 (1)
2013.08.27	5.8821	30.202	2940	Day-4 (1)
2013.08.28	5.8820	30.200	2940	Day-5 (1)
2013.08.30	5.8821	30.197	2940	Day-6 (1)
2013.09.02	5.8819	30.188	2940	Day-7 (1)
2013.09.02	5.8821	30.187	2940	Day-7 (1)
2014.05.22	5.8819	30.191	2940	Day-1 (2)
2014.05.23	5.8819	30.190	2940	Day-2 (2)
2014.05.26	5.8820	30.188	2940	Day-3 (2)
2014.06.11	5.8820	30.180	2940	Day-4 (2)
2014.06.16	5.8820	30.184	2940	Day-5 (2)

3) Lamp No. CMS 3

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
				Measurement
2013.08.21	5.8014	29.930	2940	Day-1 (1)
2013.08.22	5.8013	29.930	2940	Day-2 (1)
2013.08.26	5.8015	29.928	2940	Day-3 (1)
2013.08.29	5.8013	29.923	2940	Day-4 (1)
2013.09.02	5.8015	29.919	2940	Day-5 (1)
2013.09.03	5.8014	29.918	2940	Day-6 (1)
2013.09.03	5.8015	29.917	2940	Day-6 (1)
2014.05.22	5.8013	29.930	2940	Day-1 (2)
2014.05.23	5.8012	29.928	2940	Day-2 (2)
2014.05.26	5.8014	29.927	2940	Day-3 (2)
2014.06.11	5.8014	29.922	2940	Day-4 (2)
2014.06.16	5.8015	29.921	2940	Day-5 (2)

4) Lamp No. CMS 4

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
				Measurement
2013.08.21	5.8691	30.413	2940	Day-1 (1)
2013.08.22	5.8651	30.373	2940	Day-2 (1)
2013.08.26	5.8651	30.370	2940	Day-3 (1)
2013.08.27	5.8650	30.368	2940	Day-4 (1)
2013.08.29	5.8651	30.366	2940	Day-5 (1)
2013.08.30	5.8652	30.362	2940	Day-6 (1)
2013.09.02	5.8651	30.360	2940	Day-7 (1)
2013.09.03	5.8648	30.358	2940	Day-7 (1)

2014.05.22	5.8648	30.364	2940	Day-1 (2)
2014.05.23	5.8650	30.365	2940	Day-2 (2)
2014.05.26	5.8649	30.364	2940	Day-3 (2)
2014.06.11	5.8652	30.358	2940	Day-4 (2)
2014.06.16	5.8651	30.357	2940	Day-5 (2)

A.2.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent)

Room temperature absolute radiometer

2) Laboratory reference standards used:

Room temperature absolute radiometer

3) Description of measuring technique and procedure including number of repetition of measurements (please include a diagram):

$$I = \frac{K_{\text{m}} \times P \times C_{\text{filter}}}{A} \times L^2 \qquad \text{(A.1)}$$

Where I : luminous intensity (cd)

L : distance between the lamp and radiometer (m)

K_{m} : constant 683 (lm/W)

P : radiant power measured by the absolute radiometer (W)

C_{filter} : correction factor of the V(λ) filter

A : effective area of the absolute radiometer (m^2)

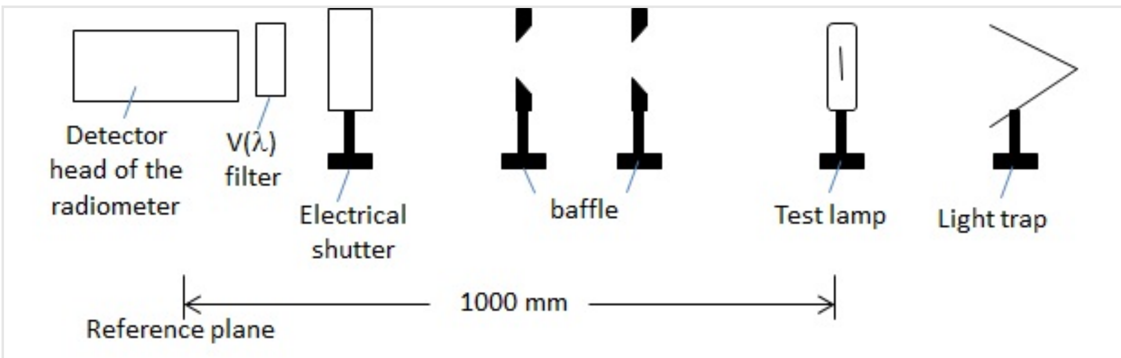


Fig. A2.1 System diagram

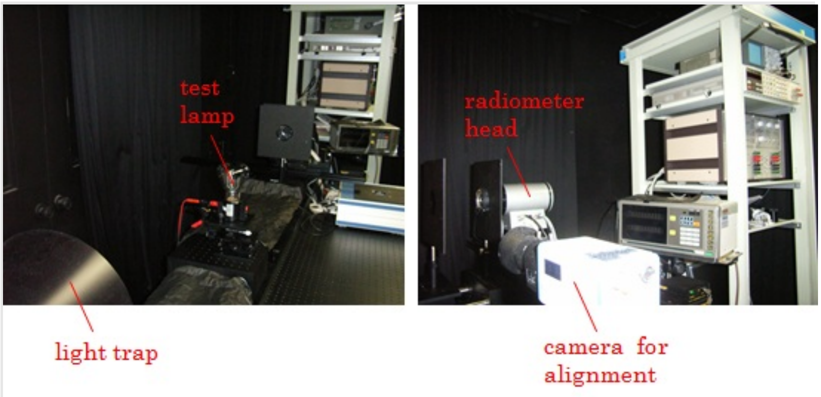


Fig. A2.2 Photos of the measurement system

4) Establishment or traceability route of primary scale including date of last realization:

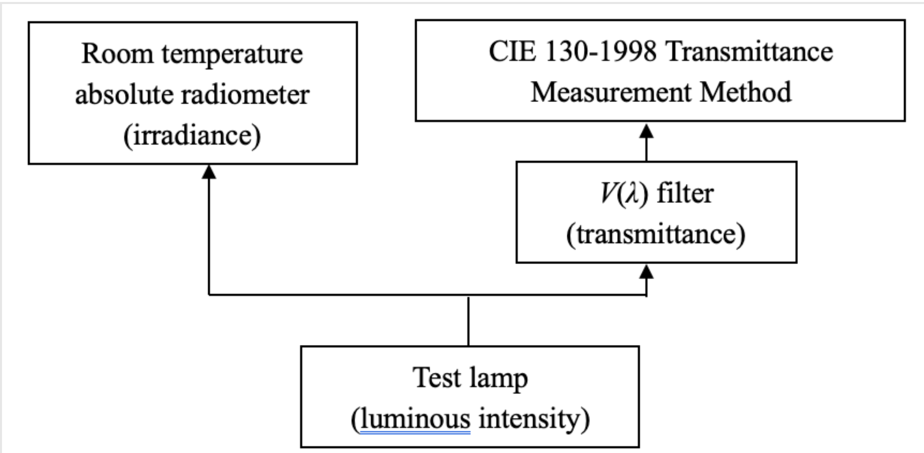


Fig. A2.3 Traceability chain

5) Description of calibration laboratory conditions: e.g., temperature, humidity etc.

- Temperature: (23.0 ± 1.5) °C
- Relative humidity: (45 ± 10) %RH

6) Operating conditions of the lamps: e.g., geometrical alignment, polarity, stray-light reduction etc.

- Geometrical alignment:
  - -base-down position
  - -the optical axis of the lamp is normal to the central of the filament plane
  - -the distance between the filament and radiometer is 100 cm to 150 cm
- Polarity: random
- Stray reduction: with baffle and light trap
- Warm up 15 min before measurement

A.2.4 Uncertainty budget of Measurement

Table A2.1 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Absolute radiometer	B	200	0.13 %
2	Electrical power	B	200	0.034 %
3	Correction factor of the $V(\lambda)$ filter	B	200	0.25 %
4	Effective area of the absolute radiometer	B	200	0.0252 %
5	Distance	B	200	0.012 %
6	Repeatability	A	9	0.2013 %
	Relative combined standard uncertainty		72	0.349 %
	Relative expanded uncertainty (with coverage factor (k) giving approximately 95 % confidence interval)			0.70 %

A.3. Standards and Calibration Laboratory (SCL)

A.3.1 Measurement results

1) 1st Round (*August - September 2013*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
130117-1	5.87523	30.42621	2856	281.09
130117-3	5.89026	30.54368	2856	277.78
130117-4	5.86606	30.53750	2857	281.10

2) 2nd Round (*December 2013*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
130117-1	5.87522	30.42404	2859	280.18
130117-3	5.89025	30.54112	2858	277.04
130117-4	5.86604	30.53324	2859	280.25

A.3.2 Record of lamp operating time

1) Lamp No. 130117-1

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
9 Aug. 2013	5.87518	30.42584	1200	Measurement #1
23 Aug. 2013	5.87531	30.42761	1200	Measurement #2
6 Sept. 2013	5.87525	30.42554	1200	Measurement #3
19 Sept. 2013	5.87519	30.42584	1320	Measurement #4
11 Dec. 2013	5.87522	30.42729	1320	Measurement #5
16 Dec. 2013	5.87522	30.42421	1260	Measurement #6
19 Dec. 2013	5.87524	30.42202	1200	Measurement #7
24 Dec. 2013	5.87522	30.42263	1200	Measurement #8

2) Lamp No. 130117-3

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
2 Aug. 2013	5.89025	30.54475	1380	Measurement #1
12 Aug. 2013	5.89026	30.54417	1380	Measurement #2
26 Aug. 2013	5.89026	30.54323	1320	Measurement #3
9 Sept. 2013	5.89027	30.54256	1320	Measurement #4
12 Dec. 2013	5.89027	30.54381	1320	Measurement #5
17 Dec. 2013	5.89026	30.54141	1200	Measurement #6
20 Dec. 2013	5.89025	30.54015	1320	Measurement #7
27 Dec. 2013	5.89022	30.53909	1320	Measurement #8

3) Lamp No. 130117-4

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
5 Aug. 2013	5.86606	30.53878	1320	Measurement #1
19 Aug. 2013	5.86607	30.53739	1320	Measurement #2
2 Sept. 2013	5.86604	30.53701	1440	Measurement #3
17 Sept. 2013	5.86604	30.53683	1260	Measurement #4
13 Dec. 2013	5.86605	30.53526	1320	Measurement #5
18 Dec. 2013	5.86606	30.53346	1200	Measurement #6
23 Dec. 2013	5.86603	30.53164	1500	Measurement #7
30 Dec. 2013	5.86601	30.53262	1200	Measurement #8

A.3.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent)

LMT I1000 photocurrent meter with P30SOT photometer head

2) Laboratory reference standards used:

1. LMT I1000 photocurrent meter with P30SOT photometer head
2. LMT C1210 Colorimeter
3. MIL 9330/10 0.1 Ω Current Shunt
4. Wavetek 1281 Digital Multimeter
5. Fluke 8508A Digital Multimeter

3) Description of measuring technique and procedure:

3.1 Measurement method

Detector based method was used to measure the luminous intensity of the standard lamps. The luminous intensity *I*, was determined by the measured illuminance *E* on the reference photocurrent meter head at a distance *r* between the lamp filament and the reference plan (the front side of the diffuser) of the photocurrent meter head. The luminous intensity was calculated as:

$$I = E \cdot r^2 \qquad \text{(A.2)}$$

All measurements were made at the distance *r* of 3.09 m on the SCL 6 m photometric bench. Figure A3.1 shows the drawing of the SCL photometric bench.

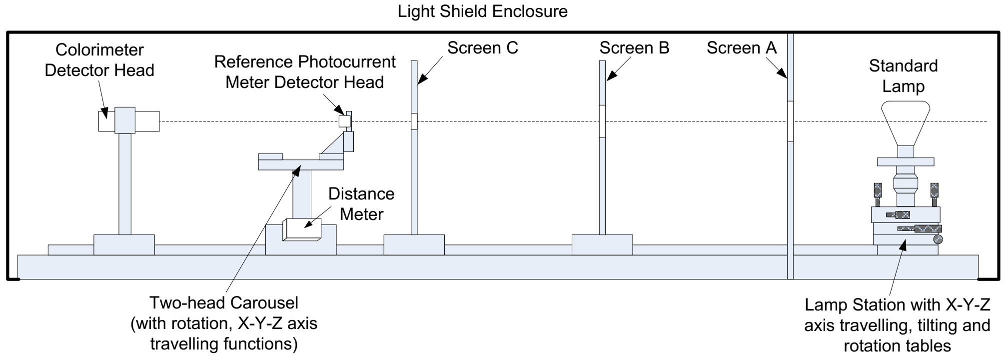


Fig. A3.1 The SCL 6 m Photometric Bench

3.2 Electrical Connections

Four-terminal connection was used on the electrical connection of the lamp. DC lamp current was applied to the terminal pair marked "I" on the lamp holder. Lamp voltage was measured at the terminal pair marked "V" on the lamp holder. The red terminal was taken as the positive terminal on both the current and voltage terminals. The lamp current was determined by the voltage-drop on a 0.1 Ω current shunt, which was connected in series with the current path. Figure A3.2 shows the details of these connections.

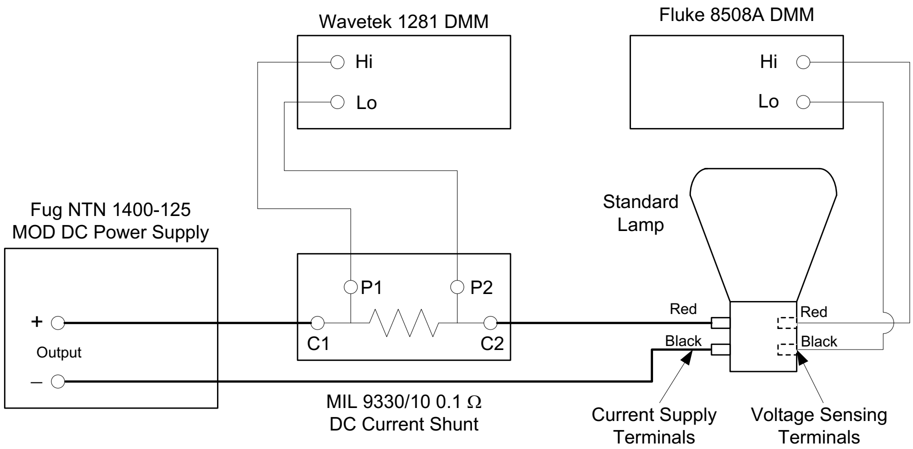


Fig. A3.2 Electrical Connections of the Measurement Circuit

3.3 Measurement procedure

The luminous intensity of each lamp was measured independently for four times on each measurement. On each measurement, the lamp current was allowed to stabilize for 10 to 15 minutes before the measurement. Each independent measurement consists of 20 sets of readings with sampling rate of 30 s per set. Each set of reading consists of the photocurrent meter reading, lamp current reading (voltage drop on the current shunt) and lamp voltage reading. The mean of the four measurement results was used as the reporting value of that lamp.

4) Establishment or traceability route of primary scale:

4.1 Illuminance Scale

The illuminance responsivity of the reference photocurrent meter was calibrated by the PTB, Germany. The last calibration date is June 2013.

4.2 DC Voltage Scale

The DC voltage measurement accuracy of the two digital meters was calibrated against a DC voltage reference, which was traceable to SCL's Josephson Array Voltage Standard System. The last realization date is 19 June 2013.

4.3 DC Resistance Scale

The DC resistance of the 0.1 Ω current shunt was calibrated against SCL's resistance standard, which was traceable to NPL UK through the calibration of two 100 Ω resistors. The last calibration date for these two 100 Ω resistors is 18 October 2012.

5) Description of calibration laboratory conditions:

All measurements were made in the Photometry and Radiometry (PR) laboratory of the Standards and Calibration Laboratory (SCL). The PR laboratory was controlled at a temperature of (23 ± 1) °C and relative humidity of (50 ± 8) % throughout the measurements.

6) Operating conditions of the lamps:

6.1 Lamp set-up

During the measurements, the lamp was placed at a base-down position on the SCL's bench. The optical axis of the lamp was set coincide with the measurement axis of the bench. The filament centre was defined as in Figure A3.3. The plane containing the filament was set vertical and orthogonal to the measurement axis of the bench.

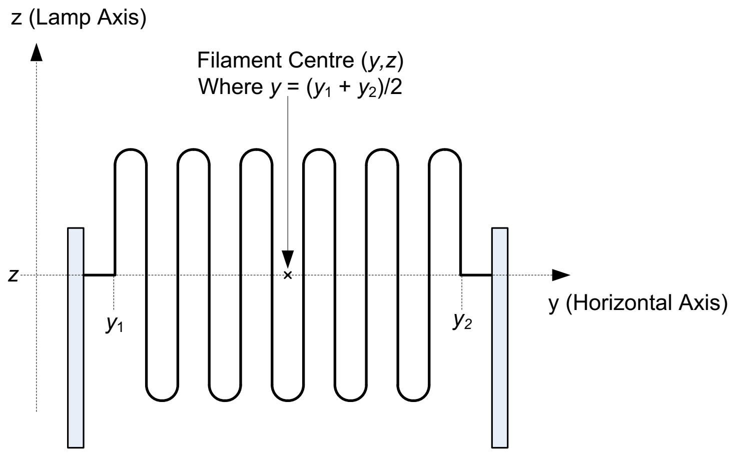


Fig. A3.3 The definition of the filament centre in the measurements

6.2 Lamp current polarity

DC lamp current was applied to the terminal pair marked "I" on the lamp holder. Lamp voltage was measured at the terminal pair marked "V" on the lamp holder. The red terminal was taken as the positive terminal on both the current and voltage terminals.

A.3.4 Uncertainty budget of Measurement

Table A3.1 Uncertainty budget for luminous intensity calibrations of transfer standards (S/N: 130117-1)

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Uncertainty in the calibration of the reference photocurrent meter by PTB.	B	∞	0.4
2	Uncertainty in the drift of the reference photocurrent meter.	B	∞	0.289

3	Uncertainty in the measured illuminance due to the resolution of the reference photocurrent meter.	B	∞	0.005
4	Uncertainty in the measured illuminance due to the standard deviation of the reference photocurrent meter readings.	A	19	0.006
5	Uncertainty in determining the distance from the lamp filament to the reference plane of the photocurrent meter.	B	∞	0.24
6	Uncertainty due to measurement uncertainty in the lamp current	B	6E+7	0.02
7	Alignment uncertainty	B	∞	0.21
8	Drift and ageing of the lamp	B	∞	0.19
9	Repeatability of the four measurements	A	3	0.043
	Relative combined standard uncertainty		1E+5	0.62
	Relative expanded uncertainty (with coverage factor (*k*) giving approximately 95 % confidence interval)			1.3

Table A3.2 Uncertainty budget for luminous intensity calibrations of transfer standards (S/N: 130117-3)

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Uncertainty in the calibration of the reference photocurrent meter by PTB.	B	∞	0.4
2	Uncertainty in the drift of the reference photocurrent meter.	B	∞	0.289
3	Uncertainty in the measured illuminance due to the resolution of the reference photocurrent meter.	B	∞	0.005
4	Uncertainty in the measured illuminance due to the standard deviation of the reference photocurrent meter readings.	A	19	0.007
5	Uncertainty in determining the distance from the lamp filament to the reference plane of the photocurrent meter.	B	∞	0.24
6	Uncertainty due to measurement uncertainty in the lamp current	B	6E+7	0.02
7	Alignment uncertainty	B	∞	0.21

8	Drift and ageing of the lamp	B	∞	0.16
9	Repeatability of the four measurements	A	3	0.032
	Relative combined standard uncertainty		3E+5	0.61
	Relative expanded uncertainty (with coverage factor (*k*) giving approximately 95 % confidence interval)			1.3

Table A3.3 Uncertainty budget for luminous intensity calibrations of transfer standards (S/N: 130117-4)

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Uncertainty in the calibration of the reference photocurrent meter by PTB.	B	∞	0.4
2	Uncertainty in the drift of the reference photocurrent meter.	B	∞	0.289
3	Uncertainty in the measured illuminance due to the resolution of the reference photocurrent meter.	B	∞	0.005
4	Uncertainty in the measured illuminance due to the standard deviation of the reference photocurrent meter readings.	A	19	0.005
5	Uncertainty in determining the distance from the lamp filament to the reference plane of the photocurrent meter.	B	∞	0.24
6	Uncertainty due to measurement uncertainty in the lamp current	B	6E+7	0.02
7	Alignment uncertainty	B	∞	0.21
8	Drift and ageing of the lamp	B	∞	0.17
9	Repeatability of the four measurements	A	3	0.031
	Relative combined standard uncertainty		4E+5	0.61
	Relative expanded uncertainty (with coverage factor (*k*) giving approximately 95 % confidence interval)			1.3

A.4. National Standardization Agency of Indonesia (BSN)

A.4.1 Measurement results

1) 1st Round (*October 2013*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
73	5.8453	30.216	2856	269.7
91	5.8462	30.083	2856	265.1
96	5.8192	29.988	2856	263.0

2) 2nd Round (*March 2014*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
73	5.8454	30.222	2850	268.9
91	5.8462	30.088	2856	264.4
96	5.8192	29.993	2843	262.1

A.4.2 Record of lamp operating time

1) Lamp No.73

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13,08,15	5.8548	30.311	1200	Determination of operating current and color temperature (before recalibration KIM-LIPI's luminous intensity standard lamp)
13,08,20	5.8548	30.311	1200	Measurement
13,10,24	5.8599	30.360	2502	Determination of operating current and color temperature (after recalibration)
13,10,25	5.8453	30.216	1200	Measurement
14,03,13	5.8554	30.222	1800	Measurement

2) Lamp No.91

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13,08,15	5.8585	30.210	1400	Determination of operating current and color temperature (before recalibration KIM-LIPI's luminous intensity standard lamp)
13,08,20	5.8585	30.210	1200	Measurement
13,10,24	5.8675	30.295	900	Determination of operating current and color temperature (after recalibration)
13,10,25	5.8462	30.083	1200	Measurement

14,03,13	5.8554	30.222	1440	Measurement

3) Lamp No.96

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13,08,15	5.8367	30.162	1400	Determination of operating current and color temperature (before recalibration KIM-LIPI's luminous intensity standard lamp)
13,08,20	5.8367	30.162	1200	Measurement
13,10,24	5.8466	30.251	800	Determination of operating current and color temperature (after recalibration)
13,10,25	5.8192	29.988	1300	Measurement
14,03,13	5.8554	30.222	1260	Measurement

A.4.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

- Photometer head
  Brand: LMT, Type: P30SOT, Serial number: 0689021
- IPh Meter
  Brand: LMT, Type: I 1000, Serial number: 0689022

2) Laboratory reference standards used:

Luminous Intensity Lamp
Brand: OSRAM
Type: Wi 41/G
Serial number: 3912

3) Description of measuring technique and procedure:

The measurement was carried out using photometer P 30 SOT s/n 0689021 traceable to KIM LIPI luminous intensity lamp Wi 41/G s/n 3912. The calibration is based on inverse square law. The illuminance produced by the subject at a distance of 2.7 meter is measured by photometer. The luminous intensity of the subject is then calculated based on the inverse square law.

$$\boldsymbol{I_v = E_v \cdot d^2 = i_v \cdot d^2 / S_v} \qquad \text{(A.3)}$$

Where, I_v is the luminous intensity of the subject, E_v is the illuminance produce by the subject at the distance of d, i_v is the measured photocurrent of the photometer and S_v is the luminous responsivity of photometer.

Using KIM LIPI luminous intensity standard lamp, the measurement carried by substitution method as the formula shown below.

$$\boldsymbol{I_{meas} = \frac{A_{meas}}{A_{std}} . I_{std}} \qquad \text{(A.4)}$$

Where I_{meas} is the luminous intensity of the subject, A_{meas} is reading of photometric current of the subject, A_{std} is reading of photometric current of standard lamp, and I_{std} is luminous intensity of the standard lamp.

4) Establishment or traceability route of primary scale:

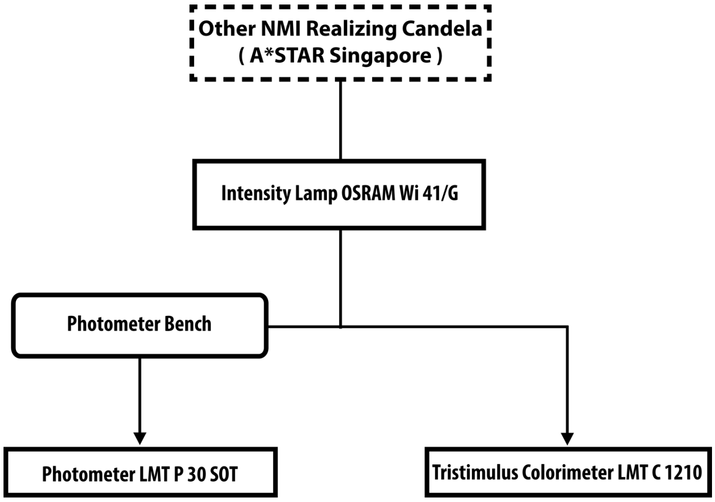


Fig. A4.1 Calibration chain

5) Description of calibration laboratory conditions:

Laboratory conditions are maintained at (23 ± 2) °C and (55 ± 5) %, monitored using thermo-hygrometer calibrated by temperature sub-division laboratory.

6) Operating conditions of the lamps:

Lamps alignment using He-Ne Laser and level used to measure the flatness. Two layers of black painted baffle and black curtain are used to reduce the stray light. The bottom of the lamp is negative pole, and the side cap is the positive pole.

A.4.4 Uncertainty budget of Measurement

Table A4.1 Uncertainty budget for luminous intensity calibrations of transfer standards (First round)

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Repeatability	A	4	0.003
2	Readability	B	50	0.000
3	Current Setting Lamp	B	50	0.002
4	Temperature	B	50	0.259
5	Photometer Linearity	B	50	0.057

6	Distance	B	50	0.015
7	Lamp Certificate	B	60	0.325
8	Stray Light	B	50	0.000
9	Alignment	B	50	0.148
10	Lamp Drift	B	50	0.144
	Relative combined standard uncertainty			0.468
	Effective degrees of freedom			162.816
	Relative expanded uncertainty (with coverage factor (*k*) giving approximately 95 % confidence interval)			0.9

Table A4.2 Uncertainty budget for luminous intensity calibrations of transfer standards (Second round)

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Repeatability	A	4	0.004
2	Readability	B	50	0.000
3	Current Setting Lamp	B	50	0.002
4	Temperature	B	50	0.235
5	Photometer Linearity	B	50	0.057
6	Distance	B	50	0.015
7	Lamp Certificate	B	60	0.325
8	Stray Light	B	50	0.000
9	Alignment	B	50	0.148
10	Lamp Drift	B	50	0.144
	Relative combined standard uncertainty			0.455
	Effective degrees of freedom			161.474
	Relative expanded uncertainty (with coverage factor (*k*) giving approximately 95 % confidence interval)			0.9

A.5. National Physical Laboratory (NPLI)

A.5.1 Measurement results

1) 1st Round (*May 2013*)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
OSRAM Wi41/G: 60	5.862	30.42	2856±20	280.8
OSRAM Wi41/G: 67	5.856	30.36	2856±20	276.3
OSRAM Wi41/G: 87	5.880	30.41	2856±20	276.6

* DT: Distribution Temperature

2) 2nd Round (*January 2014*)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
OSRAM Wi41/G: 60	5.862	30.42	2856±20	280.4
OSRAM Wi41/G: 67	5.856	30.36	2856±20	276.6
OSRAM Wi41/G: 87	5.880	30.41	2856±20	276.3

* DT: Distribution Temperature

A.5.2 Record of lamp operating time

1) Lamp No. OSRAM Wi41/G: 60

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13.05.08	5.8635	30.43	1500	Measurement
13.05.09	5.8625	30.42	1320	Measurement
13.05.22	5.8620	30.42	2160	Measurement
13.05.24	5.8621	30.42	1500	Measurement
14.01.21	5.8624	30.42	1200	Measurement
14.01.22	5.8625	30.41	1080	Measurement
14.01.23	5.8623	30.42	1050	Measurement

2) Lamp No. OSRAM Wi41/G: 67

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13.05.08	5.8543	30.33	1140	Measurement
13.05.09	5.8565	30.36	1860	Measurement
13.05.22	5.8563	30.36	1080	Measurement
13.05.24	5.8562	30.36	960	Measurement
13.05.29	5.8558	30.36	1380	Measurement

14.01.21	5.8563	30.36	1560	Measurement
14.01.22	5.8562	30.36	1260	Measurement
14.01.23	5.8564	30.36	1080	Measurement

3) Lamp No. OSRAM Wi41/G: 87

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13.05.08	5.8802	30.40	900	Measurement
13.05.09	5.8852	30.46	1050	Measurement
13.05.22	5.8803	30.41	1080	Measurement
13.05.24	5.8804	30.41	1140	Measurement
14.01.21	5.8802	30.41	1800	Measurement
14.01.22	5.8804	30.40	1140	Measurement
14.01.23	5.8803	30.42	1440	Measurement

A.5.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

LMT Photometer, B520

2) Laboratory reference standards used:

OSRAM Wi41/G intensity lamps calibrated for luminous intensity by PTB Germany

Lamps ID: (i) PTB-4.12-4057587 WI41/G OSRAM; Calibration mark – 40056PTB12

(ii) PTB-4.12-4057587 WI41/G OSRAM; Calibration mark – 40057PTB12

3) Description of measuring technique and procedure:

At NPL India, luminous intensity measurements are done by substitution method on a 3m optical bench which is housed in an enclosure 61 cm wide and 200 cm high and covered with black cloth on all four sides. The three numbers of B520 LMT photometers were calibrated, at the time of measurements, in terms of the unit of luminous intensity at approximately the color temperature of CIE illuminant A. Using substitution method, the luminous intensity scale of NPL India is transferred from the reference lamps to another group of transfer standard lamps. Optic axis of lamps and photometer is kept at about 37 cm above the bench.

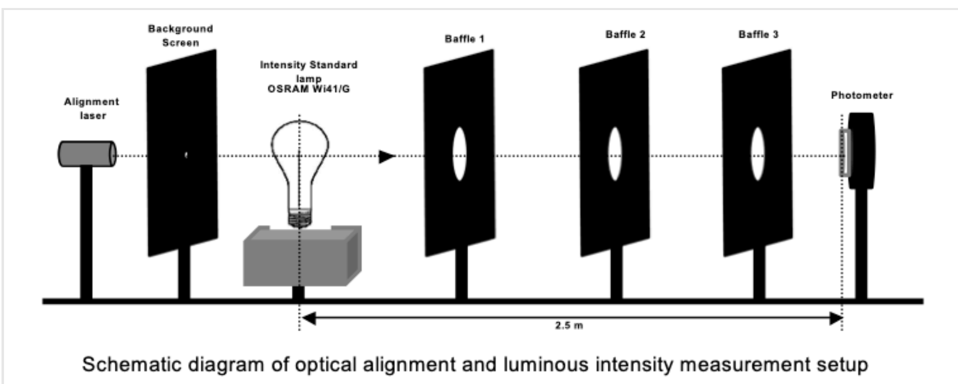


Fig. A5.1 Measurement setup for luminous intensity

The distance between the source and the detector is kept 2.5 m. A baffle of aperture size 10 cm × 23 cm is placed at the distance of about 25 cm from the lamp filament and is centered with respect to the filament. Additional baffles are placed between the source and the detector to stop any reflected or scattered light reaching the detector. Light emitted by the lamp in the direction away from the detector is absorbed with a black curtain placed 45 cm behind the lamp. The measurement setup is shown in Fig. A5.1.

The photometers used are $V(\lambda)$-corrected Si photodetectors with its spectral response (f_1' ~ 0.4%) approximately matching the CIE luminous efficacy function. It is calibrated in terms of the illuminance produced at the detector by reference standard lamp. In the substitution method, source-to-detector distances are chosen in such a way that the illuminance produced by the test lamp and the reference standard at the detector is approximately same to avoid corrections due to non-linearity of the detector.

Standards used for calibration

Reference scale for luminous intensity is maintained in the form of tungsten filament lamps of very high quality. These lamps are free from manufacturing defects, stable and their electric and photometric parameters remain unchanged over a length of time. The NPL luminous intensity scale is maintained at 2856 K and 2800 K (nominal) distribution temperatures. To check the compatibility of the scales, reference standard lamps for luminous intensity were periodically calibrated from PTB, Germany. Details of NPL reference standard lamps for luminous intensity measurements are listed in Table A5.1.

Table A5.1 NPL Reference Standards

S. No.	Manufacturer	Specifications	Identification No.
1	Osram GmbH, Germany	Wi 41/G (PTB calibrated)	40056 PTB 12
2	Osram GmbH, Germany	Wi 41/G (PTB calibrated)	40057 PTB 12

The laboratory ambient temperature during the measurements for APMP.PR-K3.a key comparison was maintained at (23 ± 2) °C with relative humidity at (50 ± 20) %.

Lamp and detector alignment

Three transfer standard lamps, after completion of first round of measurements, received from NMI Japan, the pilot laboratory, were measured one by one as was done in the first round of measurements. After proper optical alignment, the electrical current through the lamp was slowly increased to the set value kept during the first round of measurements, and the lamps were allowed to burn for about ten minutes. The current was set at the same value for each lamp, for the luminous intensity measurements.

After stabilization, the final setting of the current was done. Finally, the illuminance values at the distance of 2.5 m, for all the three lamps were measured, and the value of the luminous intensity was calculated. For repeatability, fifteen measurements were taken, however three times reproducibility was checked for each lamp.

4) Establishment or traceability route of primary scale:

We have two PTB calibrated standard luminous intensity sources (Wi 41/G OSRAM lamps) and three PTB calibrated photometers (having $V(\lambda)$ match < 0.5 %) for luminous responsivity. The lamps and the detectors in combination are used for establishing luminous intensity scale of NPLI. The traceability chart is shown as following.

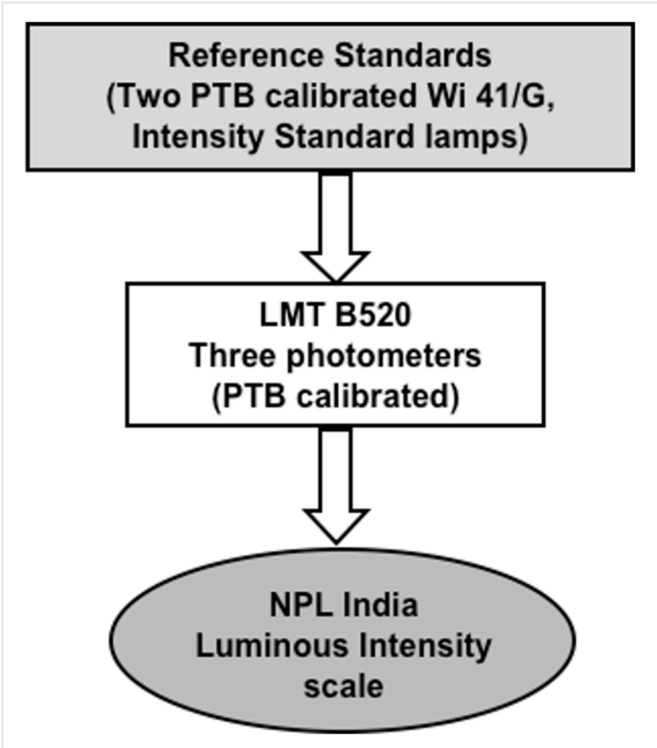


Fig. A5.2 Calibration chain

5) Description of calibration laboratory conditions:

Laboratory conditions during measurements: Temperature (23 ± 2) °C

Relative Humidity (50 ± 20) %

6) Operating conditions of the lamps:

The 3 m optical bench was put inside the black enclosure in a completely dark room. Further, stray light was minimized using three numbers of baffles between lamp and photometer. The lamps were placed at a base-down position. The optical axis of the lamp was perpendicular to the filament plane and the plane containing optical axis and lamp axis was vertical. Lamp and photometer head were aligned in a horizontal line using alignment laser. The red and black pins on the lamp base were connected to the *+ve* and *–ve* terminals, respectively of the regulated dc power supply for providing electrical current, and red and black terminals of 6.5-digit digital multimeter, respectively, for measuring lamp terminal voltage.

A.5.4 Uncertainty budget of Measurement

Table A5.2 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Uncertainty associated with the reference standard used for the calibration	B	∞	0.33
2	Uncertainty associated with random noise during transfer measurement	B	∞	0.05
3	Uncertainty associated with lamp alignment	A	9	0.05
4	Uncertainty associated with photometric distance	A	9	0.01
5	Uncertainty associated with spectral mismatch of the photometer to $V(\lambda)$	B	∞	0.05
6	Uncertainty associated with non-linearity of the photometer	B	∞	0.05
7	Uncertainty associated with stray light	A	9	0.01
8	Uncertainty associated with environmental effects such as the change of temperature and/or humidity	A	9	0.02
9	Uncertainty associated with the error in electrical parameters	A	9	0.01
10	Uncertainty associated with the drift (or ageing) of the lamp	B	∞	0.05
11	Uncertainty associated with the instability of whole calibration facilities	B	∞	0.10
	Relative combined standard uncertainty			0.36
	Relative expanded uncertainty (with coverage factor (k) giving approximately 95 % confidence interval)			0.72

The effective degree of freedom corresponded to the relative combined standard uncertainty is calculated as $\nu_{\mathrm{eff}} > 10^9$. Therefore, the coverage factor is $k = 2$.

A.6. National Metrology Institute of Japan (NMIJ-AIST)

A.6.1 Measurement results

1) 1st Round (*Month, Year*)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
#2	5.761	29.515	2799	244.53
#70	5.740	29.651	2801	246.00
#85	5.750	29.401	2799	246.36

* DT: Distribution Temperature

2) 2nd Round (*Month, Year*)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
#2	5.761	29.512	2799	244.53
#70	5.740	29.650	2801	245.90
#85	5.750	29.401	2799	246.45

* DT: Distribution Temperature

A.6.2 Record of lamp operating time

1) Lamp No. #2

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
2013/1/21	5.761	29.514	817	Measurement 1-1-1
2013/1/21	5.761	29.514	812	Measurement 1-1-2
2013/1/22	5.761	29.516	808	Measurement 1-2-1
2013/1/22	5.761	29.514	805	Measurement 1-2-2
2013/1/24	5.761	29.515	802	Measurement 1-3-1
2013/1/24	5.761	29.514	805	Measurement 1-3-2
2013/9/17	5.761	29.515	797	Measurement 2-1-1
2013/9/17	5.761	29.511	799	Measurement 2-1-2
2013/9/19	5.761	29.513	800	Measurement 2-2-1
2013/9/19	5.761	29.511	800	Measurement 2-2-2
2013/9/20	5.761	29.511	799	Measurement 2-3-1
2013/9/20	5.761	29.510	801	Measurement 2-3-2

2) Lamp No. #70

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
2013/1/21	5.740	29.652	813	Measurement 1-1-1
2013/1/21	5.740	29.651	811	Measurement 1-1-2
2013/1/22	5.740	29.651	806	Measurement 1-2-1

2013/1/22	5.740	29.651	809	Measurement 1-2-2
2013/1/24	5.740	29.650	801	Measurement 1-3-1
2013/1/24	5.740	29.650	802	Measurement 1-3-2
2013/9/17	5.740	29.650	802	Measurement 2-1-1
2013/9/17	5.740	29.649	799	Measurement 2-1-2
2013/9/19	5.740	29.650	802	Measurement 2-2-1
2013/9/19	5.740	29.649	802	Measurement 2-2-2
2013/9/20	5.740	29.651	801	Measurement 2-3-1
2013/9/20	5.740	29.650	797	Measurement 2-3-2

3) Lamp No. #85

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
2013/1/21	5.750	29.400	812	Measurement 1-1-1
2013/1/21	5.750	29.403	819	Measurement 1-1-2
2013/1/22	5.750	29.401	809	Measurement 1-2-1
2013/1/22	5.750	29.402	808	Measurement 1-2-2
2013/1/24	5.750	29.400	803	Measurement 1-3-1
2013/1/24	5.750	29.400	803	Measurement 1-3-2
2013/9/17	5.750	29.397	797	Measurement 2-1-1
2013/9/17	5.750	29.398	799	Measurement 2-1-2
2013/9/19	5.750	29.401	799	Measurement 2-2-1
2013/9/19	5.750	29.401	797	Measurement 2-2-2
2013/9/20	5.750	29.401	797	Measurement 2-3-1
2013/9/20	5.750	29.401	681	Measurement 2-3-2

A.6.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

The photometer used for the comparison measurement consists of a 100 mm diameter integrating sphere with an entrance diffuser (matte opal glass) and three filtered Si photodiodes (denoted as B, Y, and R). Spectral responsivity of the Y detector is approximated to $V(\lambda)$, whose f_1' index value is 2.1. Spectral responsivity of the B and R detector has the peak around 460 nm and 660 nm, respectively. They are used to check the distribution temperature of lamps by measuring so-called blue/red (B/R) ratio.

2) Laboratory reference standards used:

The luminous intensity scale in NMIJ is maintained with a group of standard lamps. The type of the standard lamps for that purpose is a coil-M-type luminous intensity standard lamp (55 V-330 W) manufactured by Toshiba as shown in Fig. A6.1. In this comparison, the transfer lamps (Osram Wi41/G, S/N= #2, #70 and #85) were directly calibrated with the two of the luminous intensity standard lamps that maintain the scale.

The date of last realization of the NMIJ luminous intensity scale is on January 30, 1998, and the international equivalence was confirmed by the CCPR key comparison on luminous intensity (CCPR-K3a).

Fig. A6.1 Coil-M-type luminous intensity standard lamp (55 V-330 W)

3) Description of measuring technique and procedure:

Luminous intensity of a lamp is calibrated by comparison with a group of luminous intensity standard lamps on a photometric bench. The photometric distance between the center of the lamp filament and the entrance diffuser of the photometer (i.e., reference plane) is 2.7 m. The diameter of the entrance diffuser of the photometer is 40 mm, which forms the solid angle of about 1.7×10^{-4} rad. A shielding wall lying midway of the photometric bench separates the areas for lamp operation and measurement. A hole on the wall allows the light from the lamp to pass through toward the measurement area where the photometer is placed. Aperture screens and a shutter are also placed between the lamp and the photometer. For the measurement of Osram Wi41/G lamps, a limiting aperture is used additionally in order to measure the light only goes through the rectangular mask attached on the lamp bulb. The measurement geometry including the sizes and the position of the aperture screens is shown in Fig. A6.2.

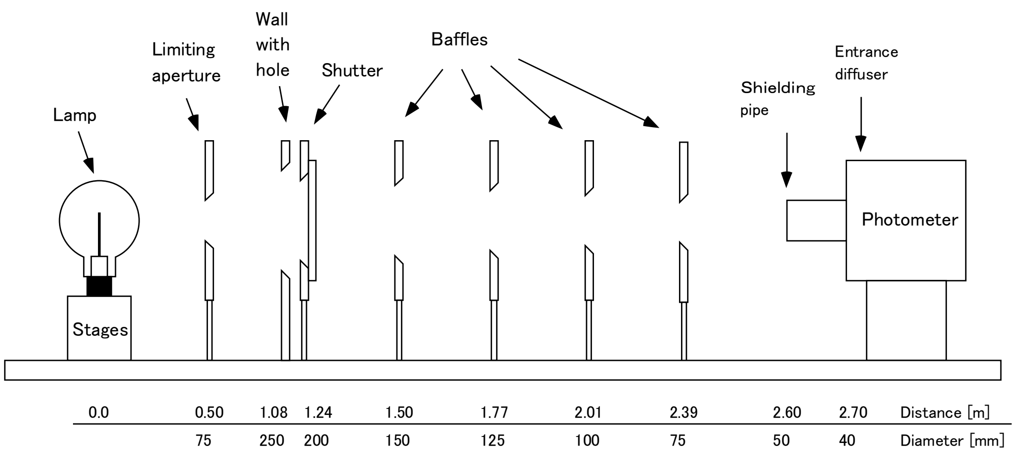


Fig. A6.2 Measurement geometry

The lamp operation area consists of a lamp alignment stage and some apparatus such as a laser and cameras. As shown in Fig. A6.3, the lamp alignment stage is composed of six stages to adjust the lamp positions along the *X*, *Y*, and *Z* axes and the rotation angles of θ_X, θ_Y and θ_Z.

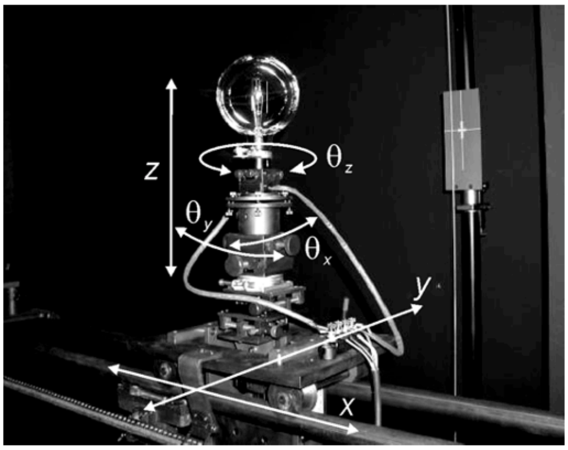


Fig. A6.3 Lamp alignment stage

For APMP.PR-K3.a comparison, three transfer lamps (T_1, T_2, and T_3) are calibrated against two luminous intensity standard lamps (S_A and S_B) maintained at NMIJ. In each calibration, the measurement data was obtained in a time-symmetrical sequence S_A, S_B, T_1, T_2, T_3, T_3, T_2, T_1, S_B and S_A). Each lamp is turned on once and the dark-subtracted photometer signal is taken, which means each lamp is turned on and measured twice in one calibration sequence. The first half of the measurement sequence (S_A, S_B, T_1, T_2, T_3) is called "Go" measurement, and the latter half (T_3, T_2, T_1, S_B and S_A) is "Return" measurement, respectively. The radiation from each lamp is detected with the photometer aligned on the photometric bench. Output signals from the photometer are measured with an 8.5-digit digital multimeter (DMM) and collected by a computer. The average of the output signals for each lamp from two measurement sequences, "Go" and "Return", is used to calculate the luminous intensity of the lamp to be measures based on the following equation.

$$I_i = \frac{1}{2}\left(k_{\mathrm{ai}} \frac{V_i}{V_{\mathrm{a}}} I_{\mathrm{a}} + k_{\mathrm{bi}} \frac{V_i}{V_{\mathrm{b}}} I_{\mathrm{b}} \right) \tag{A.5}$$

where I_i is the luminous intensity value of the *i*-th transfer lamp (T_i, i=1 to 3), I_a and I_b are the luminous intensity value of primary standard lamps (S_A and S_B), V_i, V_a, and V_b are the output signals corresponded to T_i, S_A, or S_B, respectively. k_{ai} and k_{bi} are the color correction factors, which are almost the unity due to well-approximated identical distribution temperature among compared lamps and good f_1' value of the photometer to be used for the comparison.

A schematic diagram of the NMIJ luminous intensity calibration facilities is shown in Fig. A6.4. Lamp voltage and current are measured by 8.5-digit DMMs. The lamp current is determined by measuring the voltage between the terminals of the standard shunt resistor that has a calibrated resistance. An output of a DC power supply for the lamp is regulated by a voltage/current source, whose output is controlled by the software with feedback-control using signals from the DMMs to stabilize the lamp current or voltage. An amplified output signal of the photometer is measured by another 8.5-digit DMM.

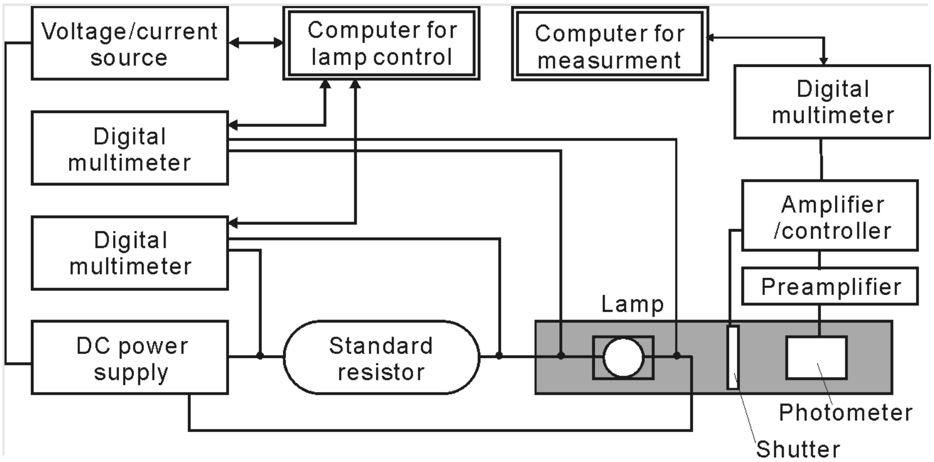


Fig. A6.4 Schematic diagram of measurement instruments

4) Establishment or traceability route of primary scale:

NMIJ luminous intensity standard is traceable to a cryogenic radiometer (CR), which is traceable to SI through electrical standards. The major calibration steps from the CR to luminous intensity standard are as follows.

- Absolute spectral responsivity measurement of a silicon photodiode against a cryogenic radiometer at several laser wavelengths
- Determination of absolute spectral responsivity of the silicon photodiode by inter- or extrapolation between or outside the discrete value of laser wavelengths with the help of a fit function
- Calibration of illuminance responsivity of a standard photometer, that consists of consists of a silicon photodiode, a precision aperture, and a $V(\lambda)$ filter by using a double-grating monochromator-based spectral responsivity calibration facility
- Calibration of luminous intensity of primary standard lamps operated at CIE illuminant A condition by using the calibrated standard photometer on a photometric bench at the distance of 2.7 m

The traceability diagram for NMIJ luminous intensity standard is outlined in Fig. A6.5.

5) Description of calibration laboratory conditions:

During the calibration, laboratory conditions are controlled as follows.

- Temperature 23.0 °C ± 2.0 °C
- Humidity 50 % ± 20 %

6) Operating conditions of the lamps:

Luminous intensity standard lamps are operated using a regulated DC power supply. Coil-M-type luminous intensity standard lamps are operated with constant-voltage mode at specified lamp polarity assigned on their quadruple terminals, two of which are used for current supply and other two are for lamp voltage measurement. Osram Wi41/G lamps are operated with constant-current mode. The lamp polarity is defined so that the negative pole is connected to the islet of the lamp base when the electrical current is supplied.

When a lamp is turned on, lamp current (or voltage) is gradually increased to the specified value in two minutes. After the lamp current reaches the fixed value, the warm-up time of 10 minutes is applied before starting measurement. When the lamp is turned off, in the same manner, the lamp current (or voltage) is gradually decreased to zero in two minutes.

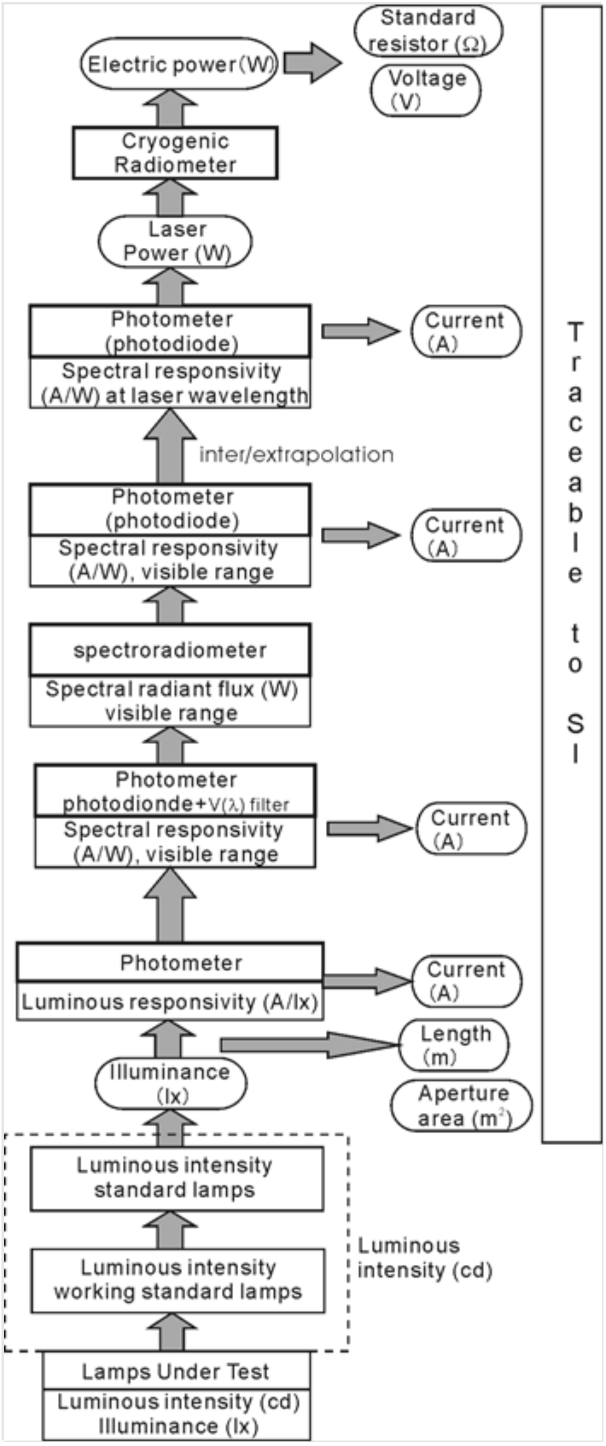


Fig. A6.5 Traceability diagram

A.6.4 Uncertainty budget of Measurement

Table A6.1 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty/ %
1	Luminous intensity of reference standard lamps	B	∞	0.256
2	Lamp current measurement	B	9	0.01
3	Photometric distance	B	9	0.02
4	Lamp alignment	B	9	0.06
5	Lamp output fluctuations	B	9	0.02
6	Ageing effect of reference standard	B	∞	0.11
	Relative combined standard uncertainty		>4000	0.29
	Relative expanded uncertainty (with coverage factor (*k*) giving approximately 95 % confidence interval)			0.58

A.7. National Metrology Institute of Malaysia (NMIM)

A.7.1 Measurement results

1) 1st Round (*September 2013*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
77	5.9470	31.760	2856	299.57
90	5.9384	31.701	2856	301.07

2) 2nd Round (*March 2014*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
77	5.9470	31.774	2856	299.92
90	5.9384	31.708	2856	301.28

A.7.2 Record of lamp operating time

1) Lamp No. 77

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
03-09-2013	5.9470	31.760	600	Measurement Day-1
04-09-2013	5.9470	31.604	600	Measurement Day-2
05-09-2013	5.9470	31.750	600	Measurement Day-3
06-09-2013	5.9470	31.780	600	Measurement Day-4
20-03-2014	5.9470	31.895	600	Measurement Day-5
10-04-2014	5.9470	31.765	600	Measurement Day-6
15-04-2014	5.9470	31.722	600	Measurement Day-7
16-04-2014	5.9470	31.721	600	Measurement Day-8
18-04-2014	5.9470	31.870	600	Measurement Day-9
15-05-2014	5.9470	31.774	600	Measurement Day-10

2) Lamp No. 90

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
03-09-2013	5.9384	31.701	600	Measurement Day-1
04-09-2013	5.9384	31.642	600	Measurement Day-2
05-09-2013	5.9384	31.780	600	Measurement Day-3
06-09-2013	5.9384	31.605	600	Measurement Day-4
20-03-2014	5.9384	31.920	600	Measurement Day-5
10-04-2014	5.9384	31.811	600	Measurement Day-6
15-04-2014	5.9384	31.832	600	Measurement Day-7
16-04-2014	5.9384	31.801	600	Measurement Day-8
18-04-2014	5.9384	31.782	600	Measurement Day-9

15-05-2014	5.9384	31.708	600	Measurement Day-10

A.7.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

Maker - National Physic Laboratory, United Kingdom; Type C306/4

2) Laboratory reference standards used:

Photometer

3) Description of measuring technique and procedure:

A laser beam is used to align the lamp towards the centre of reference photometer. The distance is determined from the centre of the lamp filament by aligning the reference plane of the photometer and record the bench scale reading. The position of standard lamp must be aligned towards the centre of reference photometer. The laser beam must reach the middle part of the surface, which can be defined as good alignment. All the instrument such as DC power supply, photometer, and amplifier are warm up for at least 1 hour before measurement begin. The power supply must be capable of providing the current and voltage required by the tungsten filament lamp. The baffles are placed on the photometric bench with the sequence from biggest one to the smallest one whereby they are placed between lamp and photometer. Then, the specific photometric distance is set by moving the photometer stage away from the lamp. The measurement is repeated at twice for each lamp. The measurements are made at a standard distance of 2.7 m.

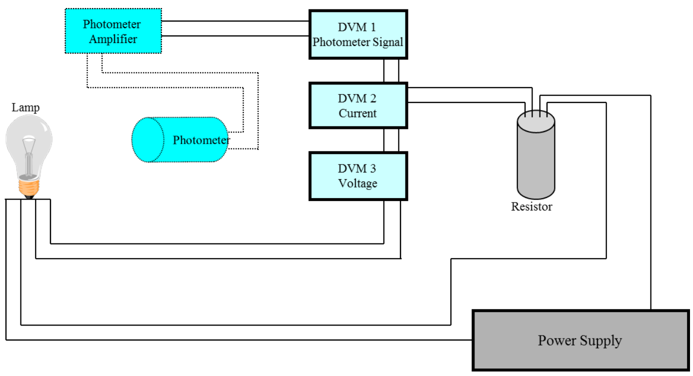


Fig. A7.1 Circuit Diagram Setup

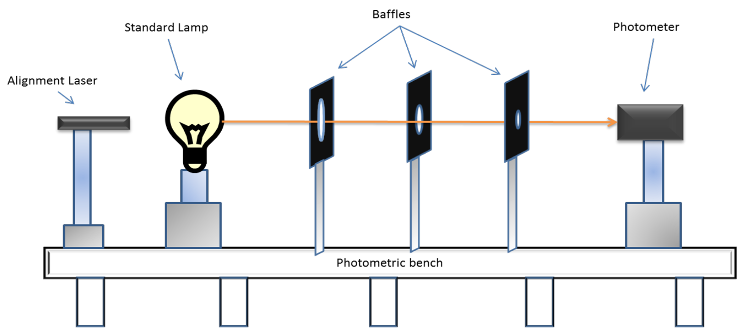


Fig. A7.2 Luminous Intensity System

4) Establishment or traceability route of primary scale:

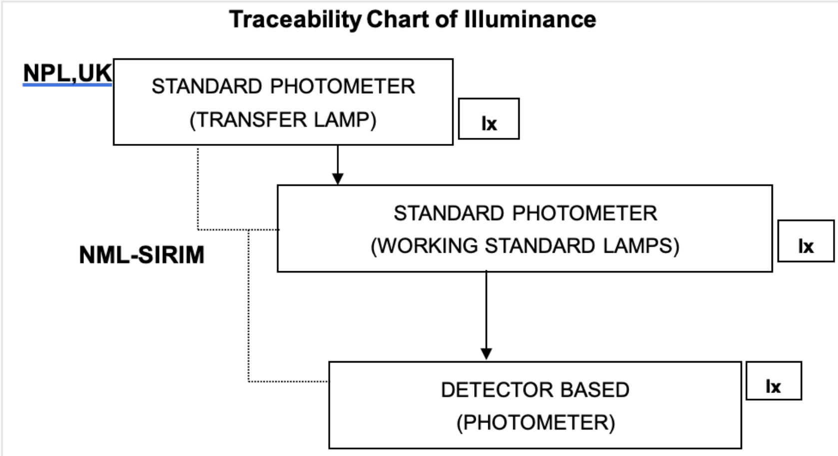


Fig. A7.3 Illuminance Traceability Chart
(Date of last realization: February 2013)

5) Description of calibration laboratory conditions:

Temperature at 23 °C ± 2 °C, Humidity at 65 % ± 5 %

6) Operating conditions of the lamps:

The standard lamp is placed at a base down position and the optical axis of the lamp should be rectangular to the filament plane and the plane containing optical axis and lamp axis should be vertical. The lamp alignment is achieved by using the scope and the lamp position is adjusted with the lamp stage in such a way that the cross wires on the scope whereby the lamp filament and the string are all in the same plane. The lamp adjustment along the photometric bench is achieved with the alignment laser. The horizontal and vertical beam from the laser alignment is used as reference line along the photometric bench. The lamp voltage is measured using four-pole technique whereby the lamp polarity is set to center as positive (+).

A.7.4 Uncertainty budget of Measurement

Table A7.1 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty/ %
1	Repeatability of Standard Lamp	A	12	0.05
2	Reproducibility of Measurement System	A	5	0.2
3	Photometer	B	50	0.4
4	Photometer amplifier	B	50	0.005
5	Digital Voltmeter	B	50	0.00002
6	Bench Scale (3 meter)	B	50	0.00056

7	Std. Resistor	B	50	0.001
	Relative combined standard uncertainty		49.27	0.45
	Relative expanded uncertainty (with coverage factor (k) giving approximately 95 % confidence interval)			0.90

A.8. Measurement Standards Laboratory (MSL)

A.8.1 Measurement results

1) 1st Round (*October 2013*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
121220-1	5.8740	30.4583	2841.7	287.31
121220-2	5.8650	30.3307	2841.0	278.50
121220-3	5.8540	30.2687	2842.4	276.48

2) 2nd Round (*March 2014*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
121220-1	5.8740	30.4575	2841.7	287.13
121220-2	5.8650	30.3314	2841.0	278.67
121220-3	5.8540	30.2695	2842.4	276.59

A.8.2 Record of lamp operating time

1) Lamp No. 121220-1

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13,09,10	5.87397	30.4627	2160	CCT Measurement
13,10,04	5.87397	30.4554	8280	LI Measurement 1
13,10,21	5.87397	30.4489 30.4594	2520	Drift Check 1
13,10,21	5.87397	30.4560	1800	Drift Check 2
13,10,22	5.87397	30.4611	2160	Group 1 - LI Measurement A
13,10,22	5.87397	30.4556	2160	Group 1 - LI Measurement B
14,03,18	5.87442	30.4614	2160	LI Measurement - Not used because power supply was returned after this in an attempt to obtain the target current.
14,03,25	5.87440	30.4588	2160	Group 2 - LI Measurement A
14,03,28	5.87418	30.4562	2880	Group 2 - LI Measurement B

2) Lamp No. 121220-2

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13,09,10	5.86504	30.3455	2160	CCT Measurement
13,10,03	5.86504	30.3411	9720	LI Measurement 1
		30.3368		Data not used
13,10,11	5.86504	30.3367	7560	LI Measurement 2
		30.3315		Data not used
13,10,14	5.86504	30.3363	6120	Drift Check 1
13,10,14	5.86504	30.3345	5400	Drift Check 2
		30.3315		
13,10,15	5.86504	30.3310	5760	LI Measurement 3 @5 m
13,10,23	5.86504	30.3323	2160	Group 1 - LI Measurement A
13,10,24	5.86504	30.3291	2520	Group 1 - LI Measurement B
14,03,18	5.86526	30.3356	2160	No measurements performed - power supply failure
14,03,25	5.86505	30.3314	1800	Group 2 - LI Measurement A
14,03,28	5.86512	30.3313	3240	Group 2 - LI Measurement B

3) Lamp No. 121220-3

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
13,09,10	5.85403	30.2738	2160	CCT Measurement 1
13,09,10	5.85403	30.2743	3600	CCT Measurement 2
13,09,24	5.85403	Not recorded	4680	CCT Measurement 3
13,10,01	5.85403	30.2686	7200	LI Measurement @2.5 m
13,10,01	5.85403	30.2664	6480	LI Measurement @5 m
13,10,16	5.85403	30.2681	2520	Drift Measurement 1
13,10,16	5.85403	30.2682	1800	Drift Measurement 2
13,10,16	5.85403	30.2674	2160	Group 1 - LI Measurement A
13,10,18	5.85403	30.2700	2520	Group 1 - LI Measurement B
14,03,17	5.85290	30.2597	2520	LI Measurement - Current too low

14,03,21	Not recorded	Not recorded	1440	Measurement failed due to lamp power supply issue.
14,03,25	5.85421	30.2694	2160	Group 2 - LI Measurement A
14,03,27	5.85429	30.2696	2520	Group 2 - LI Measurement B

A.8.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

The photometer used was designed and manufactured by the Measurement Standards Laboratory. It has a f_1' value of 1.4 % and is temperature stabilised at 29.0 °C using a temperature controller and power resistors.

2) Laboratory reference standards used:

Measurement	Instrument
Illuminance	
Detector	Primary standard 'Photometer V'.
Current to voltage converter	MSL manufactured current to voltage converter, serial number 1048-02.
DVM	HP 34401A DVM, serial number '3146A19833' traceable to MSL electrical standards.
	HP 34401A DVM, serial number '3146A14959' traceable to MSL electrical standards.
Lamp Current	
Shunt Resistor	Tinsley four-terminal 0.05 Ω shunt resistor. Type 1682, serial number 123254.
Shunt Temperature	Oregon Scientific model SA880SSWR thermistor resistance probe, serial number '194-4002'.
	Greisinger GMH 3710 digital thermometer, identified by 'GMH5I'.
	Greisinger GTF401 temperature probe identified by 'GMH5P'.
Voltage across shunt resistor	HP 34401A DVM, serial number '3146A00317' traceable to MSL electrical standards.
	HP 34401A DVM, serial number '3146A14985' traceable to MSL electrical standards.
Voltage drop across lamp	HP 34401A DVM, serial number '3146A14959' traceable to MSL electrical standards.
	HP 34401A DVM, serial number '3146A14327' traceable to MSL electrical standards.
Environmental	

Temperature Humidity	Omega iServer MicroServer identified by serial number '2210995'. Omega temperature & humidity probe, type iTHP-5-DB9, serial number 'Temp 1301'.
Distance Separation between lamp and photometer	 Komelon 10 m Steel Measuring Tape, identified by the marking 'LENGTH/2009/813' and traceable to MSL length standards.

3) Description of measuring technique and procedure:

Measurements of illuminance were made using one primary standard photometer at a fixed distance from the lamp filament.

The distance was measured by use of an alignment microscope (with cross-hairs) mounted perpendicular to the photometric bench and held in a fixed position. When the lamp or the photometer were brought into view of the microscope, such that the cross-hairs were centred on the reference plane of the photometer or the centre of the lamp filament, a pointer was set on the respective bench trolley to view a common point on the photometric bench tape. Each trolley was then moved to positions on the photometric bench to give the desired separation.

For each lamp, each measurement round consisted of two independent alignments of the lamp and photometer.

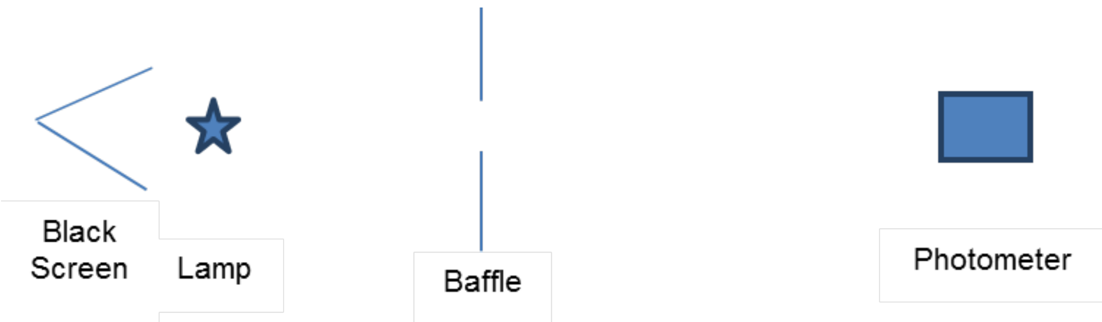


Fig. A8.1 Setup for luminous intensity measurement

Due to the design of the lamp emitting a large amount of stray light backwards, the baffle was positioned such that the photometer was only viewing an area slightly larger than the lamp window. Additionally, a blackened screen was positioned approximately 0.5 m behind the lamp to trap light emitted backwards from the lamp.

The lamp was operated at the same current as that used in the measurement of correlated colour temperature. Illuminance measurements were performed between 15 minutes and 35 minutes after the lamp was switched on.

Due to the lamp not emitting the exact illuminant A distribution, a small correction was applied to the illuminance readings to account for the spectral mismatch of the reference photometer.

Note: During the second round of measurements the power supply used to operate the lamps was not able to precisely reproduce the current setting values of the first measurement round. A correction was applied to calculate the expected luminous intensity value for the target current. This correction was based on an observed 0.1% increase in illuminance reading for a 1 mA increase in lamp operating current.

4) Establishment or traceability route of primary scale:

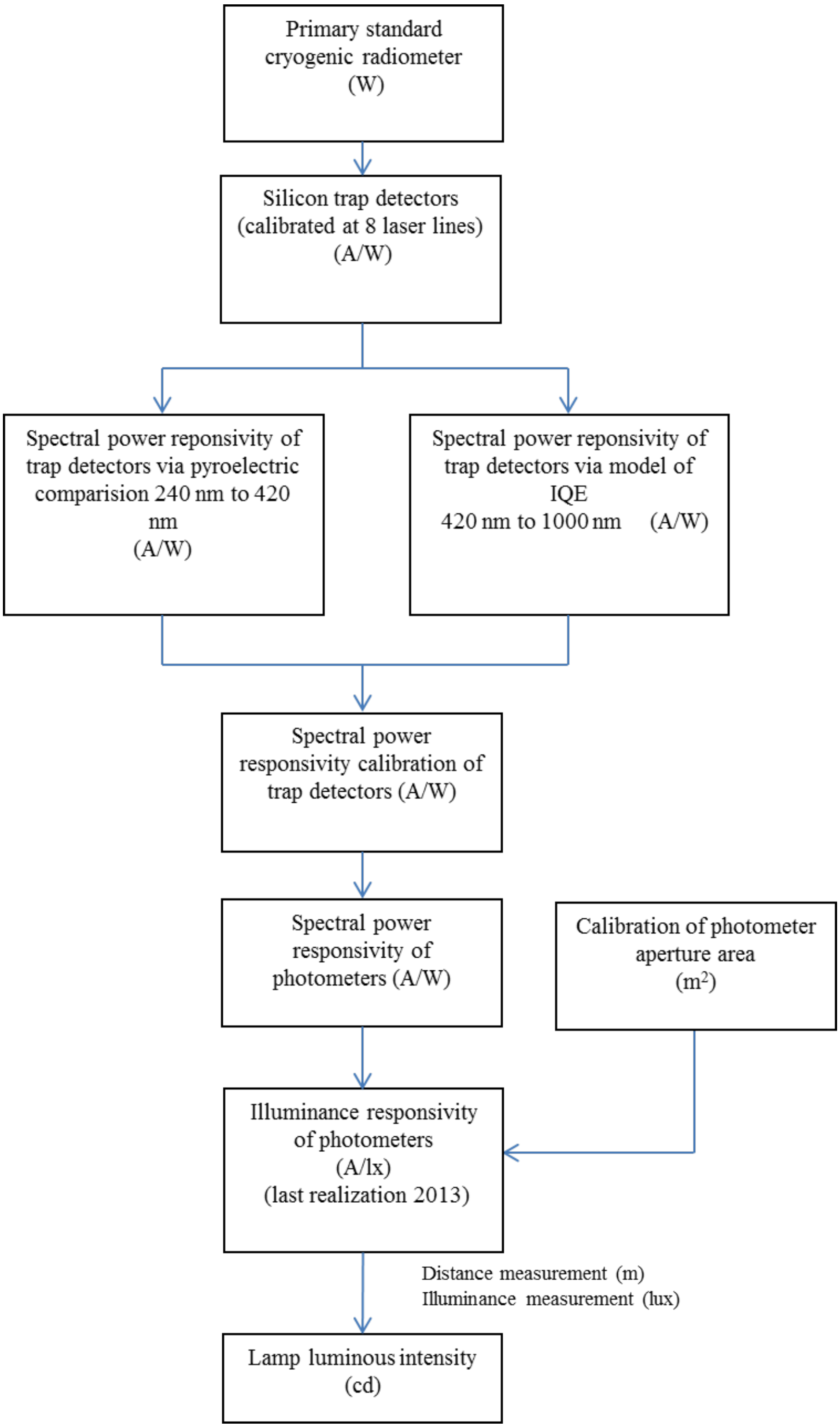


Fig. A8.2 Calibration chain

5) Description of calibration laboratory conditions:

Within the laboratory used to perform the measurements, the target temperature of 23 °C approaches the limit to which the temperature can be raised. There is no specific humidity control.

During the time period for all measurements performed for this comparison, the temperature was controlled to within 22.3 °C ± 0.9 °C and the humidity to within 52 % ± 14 %. During individual measurements runs of a lamp, the performance was better than this and is included in the calibration reports.

The primary standard photometer used has its own temperature controller therefore minimizing the effects of laboratory temperature variation.

6) Operating conditions of the lamps:

The lamp was mounted with its base down and the axis of the filament supports vertical. It was operated with the 27 mm by 27 mm window facing the photometer.

Alignment was performed by directing a laser beam parallel with the length of the photometric bench and at a height of 330 mm above the surface of the bench trolleys. The base plate and diffraction mirror were mounted on a trolley with an adjustable height post.

The orientation of the base plate was set such that the side with the diffraction mirror was closest to the photometer with the laser directed through the centre of the diffraction target. Fine adjustments were made to create a diffraction pattern on the surrounds of the laser output aperture using the reflected portion of the beam. The transmitted pattern was used to align the photometer to the lamp. A plane mirror was placed across the flat surface of the photometer to check its orientation. The lamp was then mounted on the base plate.

The red terminal on the side of the lamp marked with an ‘I’ was connected to the positive side of the power supply. The black terminal on the same side was connected to the negative side of the power supply. The lamp current was monitored using a calibrated shunt resistor. The voltage across the lamp was measured by connecting a calibrated DVM to the two terminals on the side of the lamp marked ‘U’.

Stray light was minimised by carefully positioning of a baffle such that the photometer could only view an area of the lamp that was slightly larger than the lamp window. A black screen, angled to trap backward emitted light from the lamp, was positioned around 0.5 m behind the lamp.

A.8.4 Uncertainty budget of Measurement

Table A8.1 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
	Photometer Calibration			
1	Photometer Calibration	B	70	0.1274
2	Photometer Drift	B	20	0.0217
3	Photometer Linearity	B	20	0.0050

	Illuminance Measurement			
4	Current to Voltage Converter Calibration	B	18	0.0006
5	DVM Calibration: Photometer	B	54	0.0016
6	Filament - Photometer Spacing	B	11	0.0400
7	Lamp Alignment in Measurement Plane	B	20	0.0251
8	Measurement Reproducibility	A	3	0.0018
9	Effect of Current Stability on Lamp Output	A	20	0.0176
10	Lamp Drift	B	20	0.0029
11	Photometer Temperature Stability	B	80	0.0200
12	Stray Light	B	10	0.0002
13	Spectral Mismatch of Photometer	B	20	0.0284
	Relative combined standard uncertainty		149	0.16
	Relative expanded uncertainty (with coverage factor (k) giving approximately 95 % confidence interval)			0.31

A.9. National Institute of Metrology (NIMT)

A.9.1 Measurement results

1) 1st Round (*January 2013*)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
0006	5.890	30.88	2859	287.34
0009	5.900	30.90	2844	282.17
0013	5.900	30.90	2846	277.63

* DT: Distribution Temperature

2) 2nd Round (*May 2013*)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
0006	5.890	30.96	2848	287.18
0009	5.900	30.99	2832	283.11
0013	5.900	30.97	2837	278.73

* DT: Distribution Temperature

A.9.2 Record of lamp operating time

1) Lamp No. 0006

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
1st Round				
13.01.16	5.890	30.88	1459	Measurement Day-1
13.01.17	5.890	30.88	1449	Measurement Day-2
13.01.18	5.890	30.89	1477	Measurement Day-3
2nd Round				
13.05.16	5.890	30.96	1480	Measurement Day-1
13.05.17	5.890	30.95	1484	Measurement Day-2
13.05.21	5.890	30.96	1501	Measurement Day-3

2) Lamp No. 0009

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
1st Round				
13.01.16	5.900	30.91	1517	Measurement Day-1
13.01.17	5.900	30.90	1495	Measurement Day-2
13.01.18	5.900	30.90	1528	Measurement Day-3
2nd Round				
13.05.16	5.900	31.00	1521	Measurement Day-1
13.05.17	5.900	30.98	1612	Measurement Day-2

13.05.21	5.900	30.99	1484	Measurement Day-3

3) Lamp No. 0013

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
1st Round				
13.01.16	5.900	30.90	1495	Measurement Day-1
13.01.17	5.900	30.89	1523	Measurement Day-2
13.01.18	5.900	30.89	1498	Measurement Day-3
2nd Round				
13.05.16	5.900	30.98	1525	Measurement Day-1
13.05.17	5.900	30.97	1499	Measurement Day-2
13.05.21	5.900	30.97	1512	Measurement Day-3

A.9.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

The photometer model LMT P30SC0 is used in all measurements. The photo-active element is made of Si with the light sensitive area of 30 mm in diameter. The photopic filter is of mosaic typed and gives f_1’ better than 0.8 %. It is not thermally stabilized and has the temperature coefficient better than 0.15 %/K (α_0 < -0.15 %/K) and has cosine error f_2 better than 1.5 %.

2) Laboratory reference standards used:

The laboratory reference standards are gas-filled incandescent lamps which have been calibrated by National Measurement Institute of Australia (NMIA). Their models are OSRAM Wi41/G, which is the same as that of the transfer standard lamps.

3) Description of measuring technique and procedure:

The comparison lamps were calibrated against a set of two reference standard lamps based on substitution method at the equal distance. The operating conditions of the comparison lamps were pre-determined to yield the correlated color temperature of approximately 2856 K. For each lamp, it was operated in the based-down position and its current was maintained at its pre-determined reference value throughout its operation. The report results are averaged from three rounds of measurements and in each round of measurement, the two reference standard lamps and the three transfer standard lamps being used as the comparison artifacts were measured in the reciprocal order as shown in the below figure.

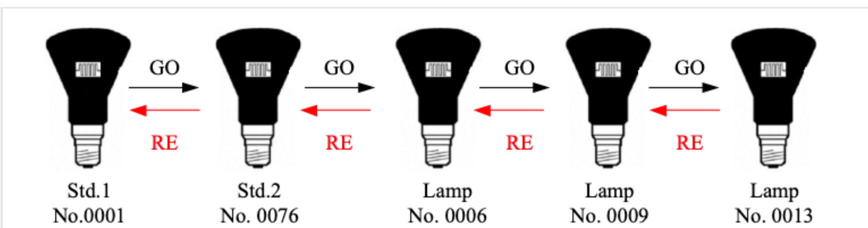


Fig. A9.1 Reciprocal timed sequence of lamps’ measurement in each round

4) Establishment or traceability route of primary scale:

The reference standard lamps used are traceable to the realization of candela at NMIA (Australia). They were last calibrated on 20 June 2012. The calibration interval is set as 3 years or 20 hours of operation, whatever comes first.

5) Description of calibration laboratory conditions:

The temperature of the laboratory room is controlled to be within 23 ºC ± 2 ºC and relative humidity of 50 % ± 15 %.

6) Operating conditions of the lamps:

1. Geometrical Alignment

   The lamp stage on the photometric bench is composing of three translational stages, one horizontal rotation stage and two tilt stages. Each lamp was installed based-down, and the center of the filament was aligned to the optical axis by the use of multi-axes alignment laser which was previously aligned to be collinear with the photometric bench. The averaged filament plane of the lamp was aligned to be perpendicular to the optical axis by the aid of two preset strings and a theodolite telescope. The two strings were preset to form a perpendicular plane to the optical axis by the use of multi-axes alignment laser and the viewing telescope was also pre-aligned.

2. Polarity

   All the lamps were operated with the polarity of negative center as shown below.

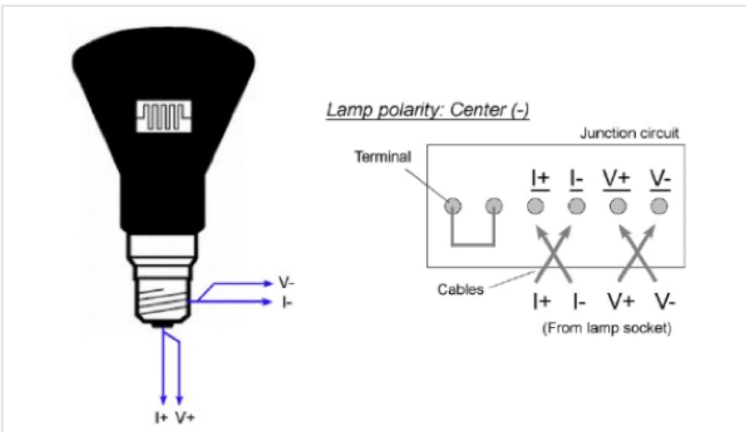


Fig. A9.2 All lamps were operated with the polarity of center base as negative

3. Stray-Light Reduction

   The laboratory room where all the measurements took place was painted matte black on its all walls to reduce the stray light. Nevertheless, the photometric bench was quite shiny so the matte-black painted baffles with circular aperture holes were employed as shown in the below figure to help reducing the stray light from other objects in the room. Additionally, to reduce the stray light further, the black cloth was used to cover shiny part of the photometric bench.

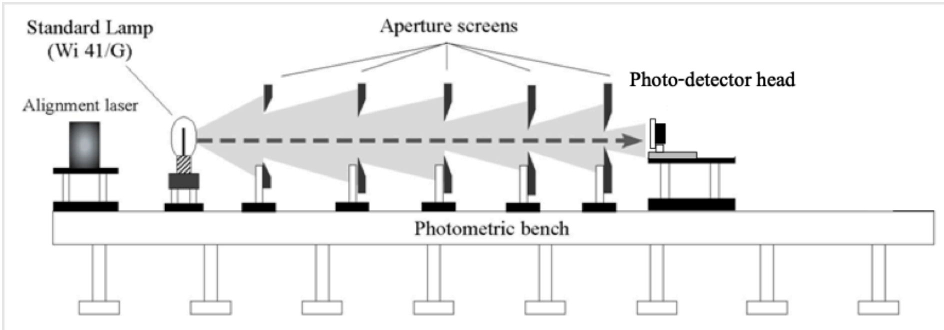


Fig. A9.3 Measurement geometry for "SIGNAL" measurement

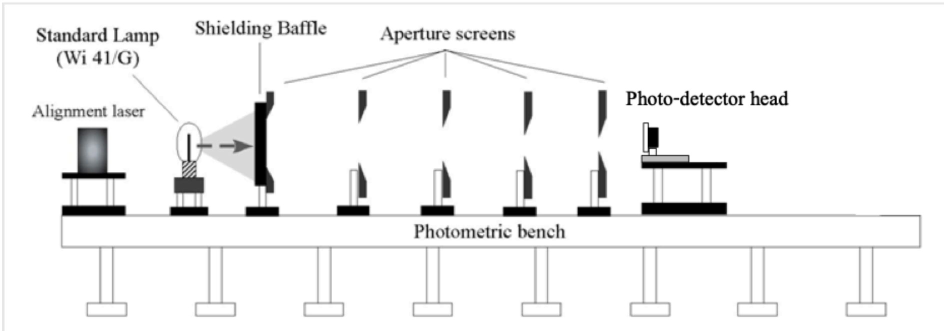


Fig. A9.4 Measurement geometry for "DARK" measurement

A.9.4 Uncertainty budget of Measurement

Table A9.1 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Repeatability of Photo-signal of Test Lamp	A	54	0.0044
2	Repeatability of Photo-signal of Standard Lamp	A	108	0.0044
3	Resolution of Photo-signal of Test Lamp	B	∞	0.0100
4	Resolution of Photo-signal of Standard Lamp	B	∞	0.0100
5	Angular Setting of Test Lamp	B	∞	0.0052
6	Angular Setting of Standard Lamp	B	∞	0.0052
7	Distance Setting of Test Lamp	B	∞	0.1155
8	Distance Setting of Standard Lamp	B	∞	0.1155
9	Current Regulation of Test Lamp	B	∞	0.0016
10	Current Regulation of Standard Lamp	B	∞	0.0065
11	Calibration of Standard Lamp	B	∞	0.1800

12	Aging of Standard Lamp	B	∞	0.2600
13	CCT Correction Factor (CCF*)	B	∞	0.0115
14	Non-linearity of Photometer	B	∞	0.0115
15	Ambient Temperature Variation	B	∞	0.0115
16	Reproducibility of Measurement	A	2	0.0282
17	Drift of Transfer Standards	B	∞	0.0866
	Relative combined standard uncertainty		>3000	0.3683
	Relative expanded uncertainty (with coverage factor ($k \approx 2$) giving approximately 95 % confidence interval)			0.74

A.10. National Metrology Centre (NMC-A*STAR)

A.10.1 Measurement results

1) 1st Round (*July 2013*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
981232-868	5.840	30.174	2838	277.0
981232-984	5.700	30.044	2840	265.4
981232-988	5.850	30.033	2841	273.2

2) 2nd Round (*October 2013*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
981232-868	5.840	30.101	2838	276.2
981232-984	5.700	30.042	2840	266.1
981232-988	5.850	30.031	2841	273.2

A.10.2 Record of lamp operating time

No burning record was provided by the participant.

A.10.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

There are three reference photometers used for the measurement (serial number: Tr1337-1, Tr1337-2, and Tr1337-3 respectively). These reference photometers are constructed using 3-element silicon trap detectors with temperature-controlled $V(\lambda)$ filter and precision aperture, based on NMC's design requirements. Fig. A10.1 shows the structure of the reference photometer head.

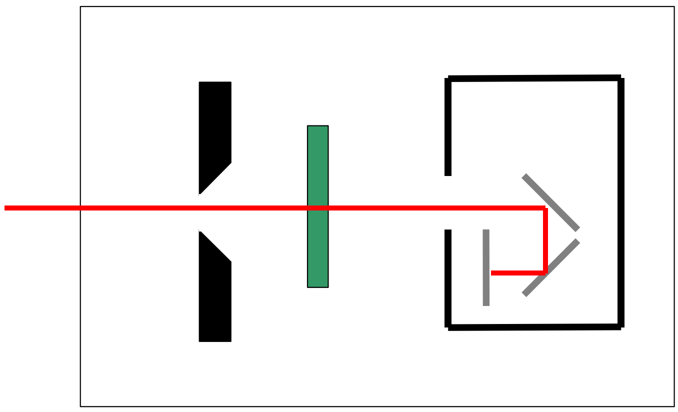


Fig. A10.1 Illustration of the structure of trap-photometer head

2) Laboratory reference standards used:

The three reference photometers are NMC's laboratory reference standards independently realized for the luminous intensity calibrations. The illuminance responsivity of the reference photometer R_v (nA/lx) can be determined by the following expression,

$$R_v = \frac{A\int S(\lambda)E(\lambda)d\lambda}{K_m\int V(\lambda)E(\lambda)d\lambda} \qquad \text{(A.6)}$$

where A (m2) and $S(\lambda)$ (nA/W) are the aperture area and the spectral responsivity of the photometer, and $E(\lambda)$ (W/m^3) is the spectral irradiance of the lamp. K_m (683 lm/W) is the luminous efficacy and $V(\lambda)$ is the spectral luminous efficiency function. If these photometers are used to measure the luminous intensity of a lamp (Illuminant A) at a distance d away from the lamp, the luminous intensity of the lamp can be expressed as

$$I_v = E_v \bullet d^2 \qquad \text{(A.7)}$$

where E_v is the illuminance produced by the lamp at the receiving surface of the photometer and E_v can also be presented as

$$E_v = y / R_v \qquad \text{(A.8)}$$

where y (nA) is the output photocurrent of the photometer.

3) Description of measuring technique and procedure:

The measurement setup is shown in Fig. A10.2 below. The measurement was done using the principle described above.

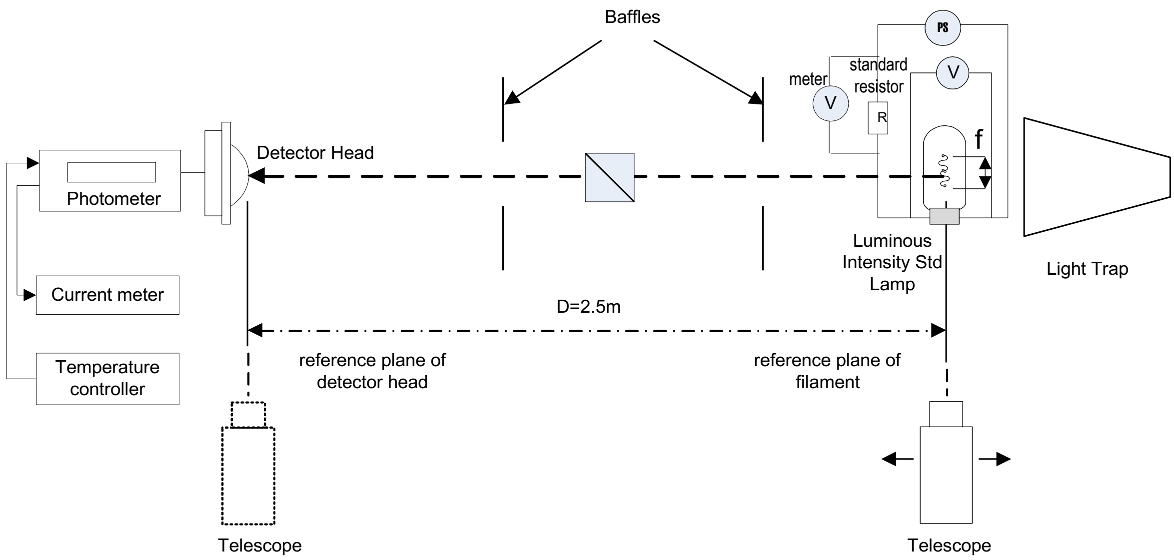


Fig. A10.2 Measurement setup

The measurement procedure is as follows:

1. Mount a He-Ne laser at one end of the optical bench and turn it on. Set up a pinhole 400mm above the bench. Align the laser's beam to pass through the centre of the pinhole. Then slide the aperture along the bench and align the laser beam so that it passes through the centre of the aperture.
2. Mount the standard lamp and trap reference photometers on the mounting stands. Put one of the trap photometers on the bench about 1.5 m away from the laser but facing the laser. Align the trap photometer so that the laser beam passes through the centre of the photometer aperture and the reflected beam from the photometer goes back to the laser. Repeat this alignment process for other two trap photometers.
3. Put a cube beam splitter in the laser path. Align it so that the laser beam is perpendicular to its surfaces and a split beam perpendicular to the original beam is produced. Set up a telescope near the bench and facing the produced perpendicular beam. Align the telescope so that perpendicular beam is co-axis with it and passing through its centre. Remove the cube once the telescope is aligned.
4. Slide the aligned photometer into the view of the telescope. Fine-tune the photometer along the bench so that its front surface falls on the cross hair of the telescope. A pointer at the base of the stand points to a reading on the scale, which is attached to the bench. Register this reading and then slide the photometer away from the laser by 1.996 m by reading the marking on the scale (the reference plane of the photometer is 4 mm behind the front surface of the photometer).
5. Put the standard lamp on the bench between the photometer and the laser and slide it into the view of the telescope. Align the lamp so that the laser beam is perpendicular to the plane of the lamp filament and passing its centre. Fine-tune the lamp along the bench so that its filament falls on the cross hair of the telescope. Register the stand position then slide the lamp towards the laser by 0.500 m. Now the distance between the reference plane of the photometer and the lamp filament is set as 2.500 m.
6. Connect the photometer to its temperature controller and the digital current meter. Switch on the controller and the current meter for stabilisation for at least an hour.
7. Set two or three baffles between the photometer and the lamp at appropriate positions, to reduce the stray light.
8. Connect the standard lamp, standard resistor, lamp power supply and the two digital voltmeters as shown in Fig A10.2. Switch on the two voltmeters for at least an hour (this can overlap with the warm up of the photometer).
9. Switch on and bring up the current of the standard lamp gradually (about 60 seconds) to the value required in its calibration report. Let the standard lamp run for 15 minutes for stabilisation.
10. Take the dark current reading and the illuminated current reading of the current meter connected with the photometer. The dark current reading is obtained by placing a small blocker (size slightly greater than the photometer detector head) in the light path.
11. Repeat steps 4 to 10 using another two trap reference photometers.
12. Each of the reference photometer was used to measure each lamp two times during one round of measurement.

4) Establishment or traceability route of primary scale:

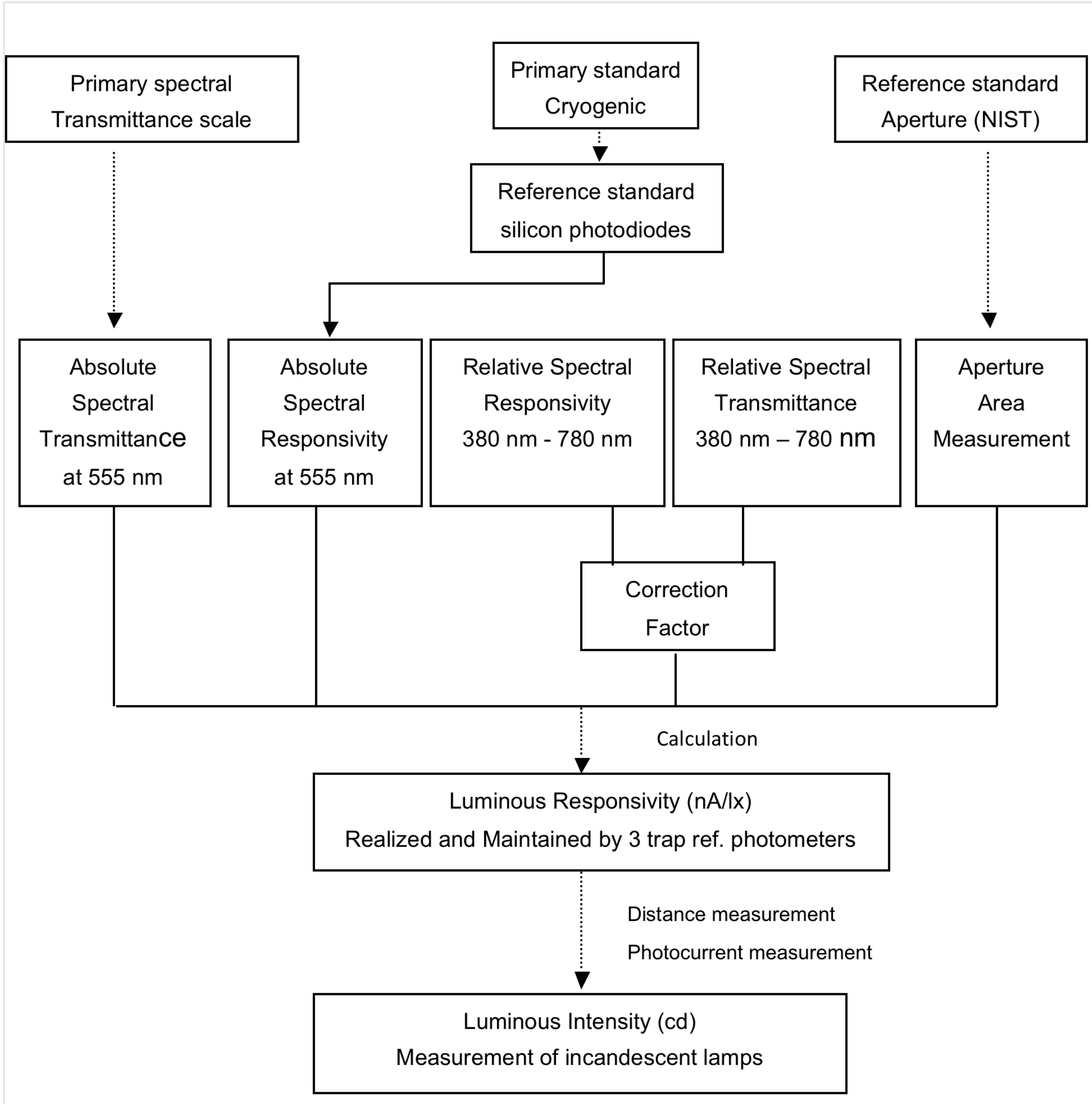


Fig. A10.3 Calibration chart

The date of last realization of the reference photometers is 19 March 2013.

5) Description of calibration laboratory conditions:

The calibration laboratory was controlled at following ambient condition:

Temperature: (23 ± 2) °C

Relative Humidity: (60 ± 10) % rh

6) Operating conditions of the lamps:

The operating conditions of the lamps are the same as described in the comparison. The electrical connection and polarity are marked on the lamp holder. Terminals with a “I” marking is for current connection. The red terminal is connected to (+) of a DC power supply, and black one to (-). Terminals with a “V” marking are for voltage measurement.

A.10.4 Uncertainty budget of Measurement

Table A10.1 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Reference photometers	B	∞	0.26
2	Drift of the reference photometers (negligible in a few months)	B	∞	0.01
3	Distance measurement	B	∞	0.02
4	Photocurrent measurement	B	∞	0.06
5	Lamp current measurement	B	∞	0.07
6	Lamp alignment	B	∞	0.01
7	Spectral mismatch of the photometer to $V(\lambda)$ (negligible after correction)	B	∞	0.01
8	Stray light	B	∞	0.01
9	Environmental effects (negligible with temperature control)	B	∞	0.01
10	Non-linearity of the photometer (negligible at the low level)	B	∞	0.01
11	Random noise	A	39	0.03
	Relative combined standard uncertainty		288357	0.28
	Relative expanded uncertainty (with coverage factor (k) giving approximately 95 % confidence interval)			0.56

A.11. Vietnam Metrology Institute (VMI)

A.11.1 Measurement results

1) 1st Round (July 2013)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
0030	5.9374	31.08	2856	289.2
0031	5.9132	30.82	2856	290.1
0037	5.9377	30.99	2856	280.2

* DT: Distribution Temperature

2) 2nd Round (October 2013)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
0030	5.9376	31.02	2856	289.0
0031	5.9135	30.80	2856	289.9
0037	5.9380	30.95	2856	280.4

* DT: Distribution Temperature

A.11.2 Record of lamp operating time

No burning record was provided by the participant.

A.11.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

Manufacture & Model: LMT P30SCT

Serial No: 01B1042

Calibrated from VMI: $U = 0.82$ % ($k = 2$)

2) Laboratory reference standards used:

Manufacture & Model: LMT P30SCT

Serial No: 10A86412

Calibrated from LMT Manufacture: $U = 0.5$ % ($k = 2$)

3) Description of measuring technique and procedure:

Measurement method of luminous intensity standard lamp: measurement at a specified distance (d = 3.0 m) using a calibrated standard photometer (LMT P30SCT; S/N 01B1042) and a calibrated spectroradiometer (CS-2000A).

4) Establishment or traceability route of primary scale:

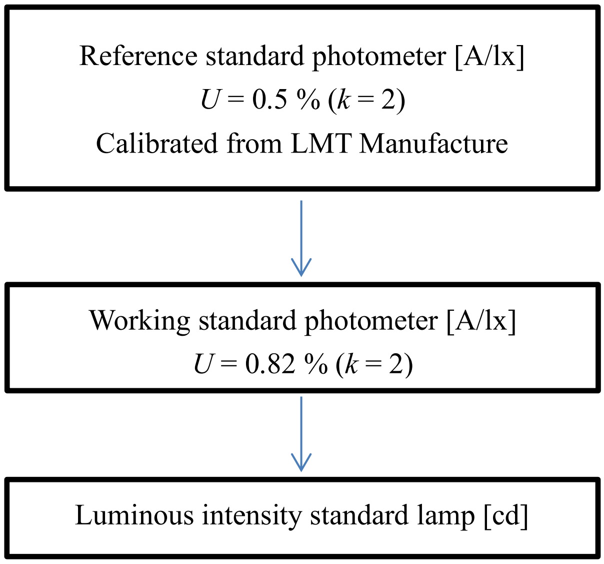


Fig. A11.1 Calibration chain

5) Description of calibration laboratory conditions:

Temperature: (23 ± 2) °C

Relative Humidity: (45 ± 15) %RH

6) Operating conditions of the lamps:

The lamp polarity is (-)

The lamp operating condition is constant - current mode (CC)

Color temperature: 2856 K

A.11.4 Uncertainty budget of Measurement

Table A11.1 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Repeatability of the standard photometer	A	10	0.10
2	Alignment of the standard photometer	B	infinity	0.08
3	Lamp-Current regulation	A	infinity	0.07
4	Stray light	B	infinity	0.12
5	Calibration of the reference photometer	B	infinity	0.25
6	Repeatability of the test photometer	A	10	0.12
7	Alignment of the test photometer	B	infinity	0.09

8	Spectral mismatch correction	A	infinity	0.11
	Relative combined standard uncertainty		>1000	0.41
	Relative expanded uncertainty (with coverage factor (k) giving approximately 95 % confidence interval)			0.82

A.12. National Metrology Institute of South Africa (NMISA)

A.12.1 Measurement results

1) 1st Round (*December 2013*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
"24" 4595 PTB 09	5.824	30.258	2859	269.7
"39" 4596 PTB 09	5.892	30.828	2864	284.9
"42" 4597 PTB 09	5.880	30.727	2865	277.4

2) 2nd Round (*May 2014*)

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
"24" 4595 PTB 09	5.824	30.242	2841	270.1
"39" 4596 PTB 09	5.892	30.816	2853	285.0
"42" 4597 PTB 09	5.880	30.713	2848	275.7

A.12.2 Record of lamp operating time

1) Lamp No. "24" 4595 PTB 09

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
11.12.2013	5.824	30.247	1500	CCT measurement -1
12.12.2013	5.824	30.248	1200	CCT measurement -2
17.12.2013	5.824	30.260	1680	Measurement -1
17.12.2013	5.824	30.254	1260	Measurement -2
18.12.2013	5.824	30.257	1020	Measurement -3
18.12.2013	5.824	30.257	780	Measurement -4
18.12.2013	5.824	30.262	960	Measurement -5
06.05.2014	5.824	30.247	1260	CCT measurement -1
19.05.2014	5.824	30.241	1200	Measurement -1
20.05.2014	5.824	30.243	1200	Measurement -2

2) Lamp No. "39" 4596 PTB 09

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
11.12.2013	5.892	30.823	1200	CCT measurement -1
12.12.2013	5.892	30.808	1200	CCT measurement -2
18.12.2013	5.892	30.828	840	Measurement -1

18.12.2013	5.892	30.823	720	Measurement -2
18.12.2013	5.892	30.827	660	Measurement -3
19.12.2013	5.892	30.829	780	Measurement -4
19.12.2013	5.892	30.832	780	Measurement -5
06.05.2014	5.892	30.823	1320	CCT measurement -1
19.05.2014	5.892	30.817	1200	Measurement -1
20.05.2014	5.892	30.816	1260	Measurement -2

3) Lamp No. "42" 4597 PTB 09

Date	Current (A)	Voltage (V)	Operating time (s)	Activity
12.12.2013	5.880	30.717	900	CCT measurement -1
12.12.2013	5.880	30.725	900	CCT measurement -2
17.12.2013	5.880	30.730	840	Measurement -1
17.12.2013	5.880	30.726	720	Measurement -2
18.12.2013	5.880	30.729	780	Measurement -3
18.12.2013	5.880	30.727	780	Measurement -4
18.12.2013	5.880	30.725	720	Measurement -5
06.05.2014	5.880	30.719	1500	CCT measurement -1
19.05.2014	5.880	30.716	1800	Measurement -1
20.05.2014	5.880	30.710	1200	Measurement -2

A.12.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

LMT Photometer, partial-filtering type.

2) Laboratory reference standards used:

Si-trap detectors (3-trap design).

3) Description of measuring technique and procedure:

i. Color Temperature

The correlated color temperature of each lamp was measured with a filter-photometer. The measurement setup consisted of the lamp in use, a diffuse reflector standard, the filter photometer, and optical baffles, all mounted on an optical bench.

Each lamp was aligned perpendicular to the diffuse reflector standard at a distance of approximately 1 m. The filter-photometer head was aligned at an angle of ~45º to the reflector standard. The lamp filament, diffuse reflector standard and filter-photometer head were aligned in one horizontal plane. In order to reduce stray light, baffles were placed between the lamp and the diffuse reflector standard as well as a baffle tube with a ~45° extension tube between the filter-photometer and the reflectance standard. Refer to Fig. A12.1 for the experimental layout.

The reported CCT value for each lamp is the result of the average of ten measurements. The operating current and voltage of the respective lamps were determined for the reported color temperatures.

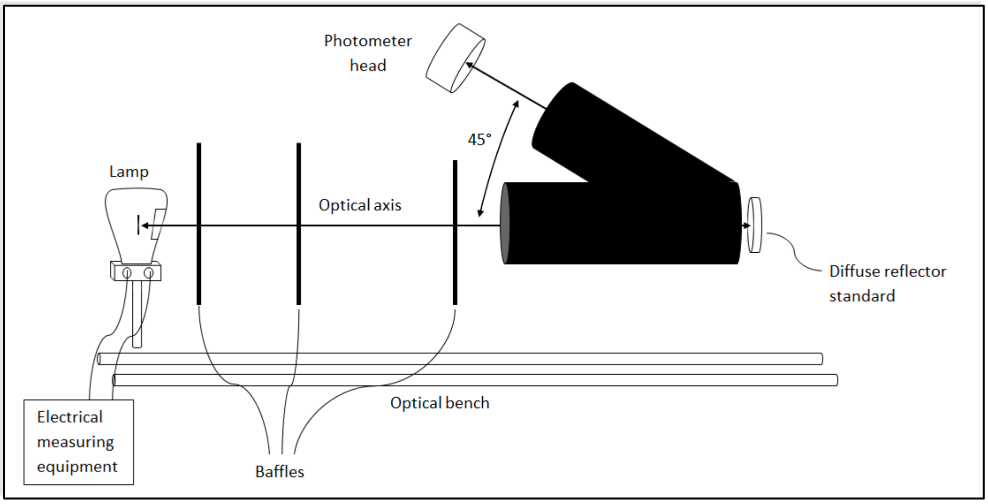


Fig. A12.1 Schematic diagram of experimental setup for colour temperature

ii. Luminous Intensity

The lamps were connected to the power supply according to the polarity as indicated on the lamp terminals. Each lamp was aligned perpendicular to the partial-filtering photometer at a distance of 2.7 m. In order to reduce stray light, baffles were placed between the lamp and the photometer. Refer to Fig. A12.2 for the experimental layout. Five measurements per lamp were performed during each measurement set. The lamps were re-positioned and aligned and powered on and off between the different sets. The reported luminous intensity value is the average of the two sets.

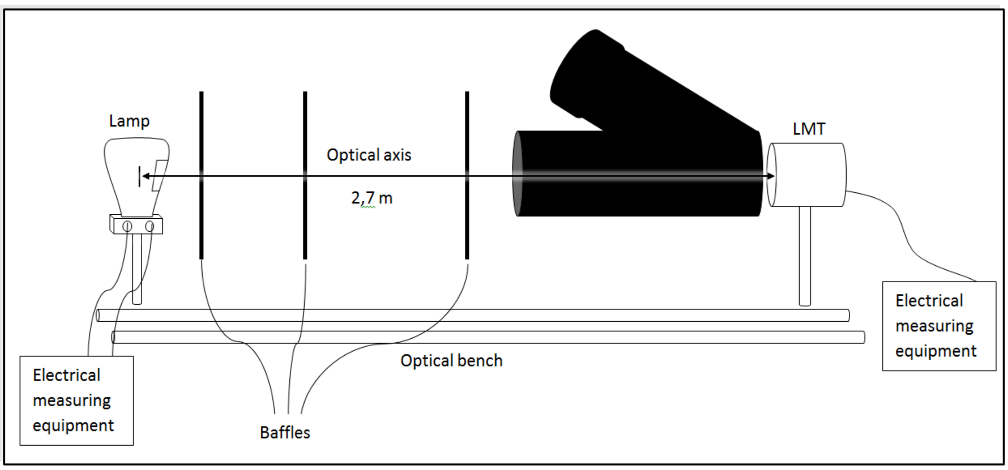


Fig. A12.2 Schematic diagram of experimental setup for luminous intensity

4) Establishment or traceability route of primary scale:

The Si trap detectors were calibrated at the National Physical Laboratory (UK).

5) Description of calibration laboratory conditions:

The temperature in the laboratory during measurements was:

CCT:

Average Temperature = 21 °C

Average Humidity = 39 %RH.

Luminous Intensity:

Average Temperature = 21 °C

Average Humidity = 40 %RH.

6) Operating conditions of the lamps:

The current and voltage were gradually adjusted when powering the lamps up and down. The operating current of the lamps were adjusted to the current values determined during the CCT measurements. The lamps were allowed to stabilize for 10 minutes before measurements were performed. The current and voltage during the measurement period were recorded at regular intervals.

A.12.4 Uncertainty budget of Measurement

Table A12.1 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Reference standard (photometer)	B	Infinite	0.6500
2	Non-linearity of photometer	B	12,50	0.0577
3	Temperature dependence of photometer	B	12,50	-0.0450
4	Spectral mismatch factor of photometer	B	12,50	0.1382
5	Drift of photometer	B	12,50	0.1600
6	Gain setting of photometer	B	12,50	0.0416
7	Distance measurement (photometer and optical bench)	B	Infinite	0.0428
8	Distance measurement (lamp filament with regards to reference plane)	B	Infinite	0.0428
9	Lamp fluctuations during operation	A	Infinite	0.0196
10	Electrical noise on photometer signal	A	Infinite	0.0047
11	Electrical measurement – standard resistor	B	Infinite	0.0558
12	Electrical measurement – voltmeter, photometer	B	Infinite	0.0009

13	Electrical measurement – voltmeter, supply current	B	Infinite	0.0128
14	Lamp orientation	A	Infinite	0.1424
15	Lamp current setting stability	A	Infinite	0.0101
16	Stray light	B	12,50	0.0229
17	Repeatability	A	149	0.0096
18	Drift of lamps	A	Infinite	0.1336
	Relative combined standard uncertainty (k = 1)			0.73%
	Relative expanded uncertainty (with coverage factor (*k* = *2*) giving approximately 95 % confidence interval)			1.5 %

A.13. National Institute for Standards (NIS)

A.13.1 Measurement results

1) 1st Round (*December 2012*)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
E13	5.990	32.11	2856	290.3
E14	6.028	32.08	2856	280.9
E15	5.854	32.33	2856	281.7
E17	6.013	31.64	2856	278.2

* DT: Distribution Temperature

2) 2nd Round (*December 2013*)

Lamp No.	Current (A)	Voltage (V)	DT* (K)	Luminous Intensity (cd)
E13	5.990	32.07	2856	288.6
E14	6.028	32.03	2856	281.2
E15	5.854	32.26	2856	280.8
E17	6.013	31.61	2856	276.9

* DT: Distribution Temperature

A.13.2 Record of lamp operating time

No burning record was provided by the participant.

A.13.3 Description of the measurement facility

1) Make and type of the photometer (or equivalent):

Two photometers were used for the measurements. The type of photometer used is **LMT PA 11.3 FOT** photometer head (provided by **LICHT MESSTECHNICK GMBH -Berlin)**. The photometer contains fine adapted to the spectral luminous efficiency $V(\lambda)$ silicon photoelement with light sensitive surface of 11.3 mm diameter. It has **no diffuser**. The reference plane of the photometer is the outside of the turbid material, which is glass with chrome coating precise aperture. The photometer is thermostatic stabilized and is kept constantly at about 35 $^{\circ}$C.

The serial numbers of these photometers are **PA 11.3/02A7512 & PA 11.3 /02A7513**. The relative spectral responses of both photometers were measured at the Radiometric division (NIS-Egypt).

2) Laboratory reference standards used:

1. Two standard Lamps used as reference standards

These are **OSRAM Wi 41G** tungsten filament lamp 200 W, purchased and calibrated at NPL for color temperature and luminous intensity. The reported expanded uncertainty (*k*=2 & 95 %

confidence level) is ±0.7 % for luminous intensity and 2856 K ± 11 K for color temperature. The lamps were marked with the numbers **C728-43 and C608-20.**

2. Two LMT photometers

(As described above) calibrated for relative spectral response.at Radiometry division NIS-Egypt.

3. LMT digital photocurrent meter Type I1000 serial no. 02A7511.

It is a high precision instrument for measuring the electric current of the photodetector. It is 4.5-digit display ranges from 15 mA to 10 pA. It includes a power supply to operate thermostatic stabilized LMT photometer head. The current meter has a BCD output and also an IEEE-488 interface. The current meter was calibrated at Electrical Metrology division -The National Institute for Standards in Egypt (NIS). The calibration is done by connecting a standard precision DC current-source the I1000 LMT meter to was connected to the input of the LMT instrument. A test current of about 0.9 -times of the full-scale value of each measuring range was fed into the current meter. The uncertainty of the calibration was < ±0.2 % of the tested current and traceable to NIST (USA).

4. Power supply

A programmable high stability Dc current source, type **OL 83A** manufactured by Optronik Laboratories. The power output of this power supply ranges between 10 & 1000 Watts while the maximum current output is 8.4 Amps DC with current resolution 0.001 Amps. The power supply was checked for stability after 30 minutes warm-up period, by using a 200 W lamp, standard resistor, and calibrated multimeter. The output current stability at 6.00 A is less than ±0.02 %.

5. Digital multimeter

8.5 digital multimeter **Fluke 8508A** was used to measure the voltage across the standard resistance, and deducing the current through the lamp. The voltmeter has been calibrated at the Electrical Metrology Division at The National Institute for Standards in Egypt (NIS) with an uncertainty ±0.02 %. The calibration is traceable to National Institute for Standards and Technology (NIST-USA).

6. Digital multimeter

6.5 digital multimeter model 2000-20 was used to monitor the volt across the lamp. The voltmeter has been calibrated at the Electrical Metrology Division at The National Institute for Standards in Egypt (NIS) with an uncertainty ±0.02 %. The calibration is traceable to National Institute for Standards and Technology (NIST-USA).

7. Standard resistance

Standard resistance Tinsley 0.1ohm-22A of type 1862. The resistance has four terminals. Two current terminals are connected in series with the lamp and power supply. The two other terminals are used to monitor the voltage across the resistance, which in turn determines the current through the circuit. The resistor has been calibrated at the Electrical Metrology Division at The National Institute for Standards in Egypt (NIS) with an uncertainty ±0.003 %. The calibration is traceable to National Institute for Standards and Technology (NIST-USA).

Auxiliary Equipment

- Optical table of length 4.8 m from Standa
- Optical rails 3 m length, optical mounts, rail carriers, tilt, and rotational stages.
- Solid-state laser

- Four terminal E27 screw base socket used for the lamps, provided by LMT
- He-Ne Laser
- Telescope

3) Description of measuring technique and procedure:

1. Color temperature calibration

The transfer Osram lamps used for measurements Wi 41G have been first adjusted to CCT of 2856 K ± 20 K. This is performed by comparing each lamp with a standard certified lamp of CCT 2856 K ± 11 K calibrated at NPL. An integrating sphere of diameter 50 cm and a spectroradiometer Minolta CS1000A are used to monitor correlated color temperature for both the certified and measured lamps. The current of the transfer lamp is gradually increased until the lamp color temperature value gives the same as the standard lamp. Then the current & volt of the considered lamp were recorded.

The following table indicates the lamp and voltage for each transfer lamps.

Table A13.1 Lamp operating conditions

lamp no.	current A	voltage V	Distr. Temp.
E13	5.990	32.11	2856
E14	6.028	32.08	2856
E15	5.854	32.33	2856
E17	6.013	31.64	2856

2. Measuring luminous intensity

The base of lamp is mounted and screwed on a black anodized tilt and rotation stage to enable alignment along the optical axis X and the longitudinal axis Z (perpendicular to X). The rotation adjusts the Y axis to be perpendicular to the plane containing X and Z axis (see alignment procedure below). The lamp, the detectors and the alignment laser are mounted on stands that allow rotation, movement in all x, y, and z axes, and flipping in the direction of z.

The lamps were operated by constant-current source OL83. Each lamp was operated at its specified current which was monitored by a 0.1 Ω high-precision shunt resistor and. digital voltmeter. Fluke. The light source and the photometers were aligned to the same optical axis using the alignment laser. Lamp current was ramped up slowly in around a few minutes until it reaches the specified operating value. The lamps were allowed to stabilize for minimum 20 minutes before taking measurements. This time is sufficient. Two LMT photometers were mounted on a translation stage, which allowed displacement perpendicular to the optical axis. The photometers were optically aligned using the laser beam, which directed to the center of the photometer aperture. The photometer was also aligned so that the reflected beam from a thin mirror attached to the surface of the detector, returned back to the alignment laser. The distance of measurement was about 3 m, measured between the filament plane of the lamp and the reference plane of the detector. 3 stray-light screens between the light source and the photometers were used at distances of about 0.4 m, 1.5 m, and 2.8 m from the lamp.

An iris diaphragm included was placed about 20 cm from the photometer. The diameter of the aperture was adjusted such that its shadow line was just outside the largest entrance aperture of the photometers. The filament has to be fully visible to the detector input at applied distances. The influence of an inclination of the photometers with respect to the optical axis was studied by introducing such an inclination purposely and recording the percentage change in luminous intensity. It was found that an inclination about 5° causes less than 0.1 % of luminous intensity values were obtained with the help of a LMT I1000 photocurrent meter. The output measured current, is proportional to luminous intensity of the lamp used. Two of the standard lamps (C608-20 and C728-43) were used in the measurements.

Table A13.2 Standard lamps

ID	Color temperature	Current	Voltage	Luminous intensity	Uncertainty in luminous intensity (*k*=2)	Uncertainty in color temperature (*k*=2)	Traceability
C 608-20	2856 K	5.922 A	30.92 V	281.2 cd	±0.7 %	±11 K	NPL
C728 -43	2856 K	5.911 A	30.80 V	286.3 cd	±0.7 %	±11 K	NPL

The luminous intensity values of the lamps were determined by substitution method. If a standard lamp of luminous intensity L_s is measured photodetector gives a current i_s, and the current obtained by a measured lamp (for the same detector) is i_m, then the luminous intensity of the measured lamp L_m is

$$\frac{i_m}{i_s} \times L_s \qquad \text{(A.9)}$$

For each lamp, a measurement cycle consists of five back and forth displacements of the translation stage, placing the two photometers in turn on the axis of the bench. Measurements were taken at each position, back and forth. The corrected current values were obtained after subtracting the dark current for each measurement.

Measurements were scheduled to be made for both standard lamps C 608- 20& C728 -43.
The lamps were interchanged as the following sequence:

transfer lamp (ex. E13)
Standard lamp C 608- 20
transfer lamp
Standard lamp C728 -43
transfer lamp

Realignment of the lamp and photometers has been performed when the lamp changed.

Applying equation (1), we get 2 averaged values for each sequence. One sequence of measurements takes one day. Each lamp measured in 10 days of measurements, getting 20 luminous intensity values. 20 measurement values were averaged to get a luminous intensity value for a specified measured lamp.

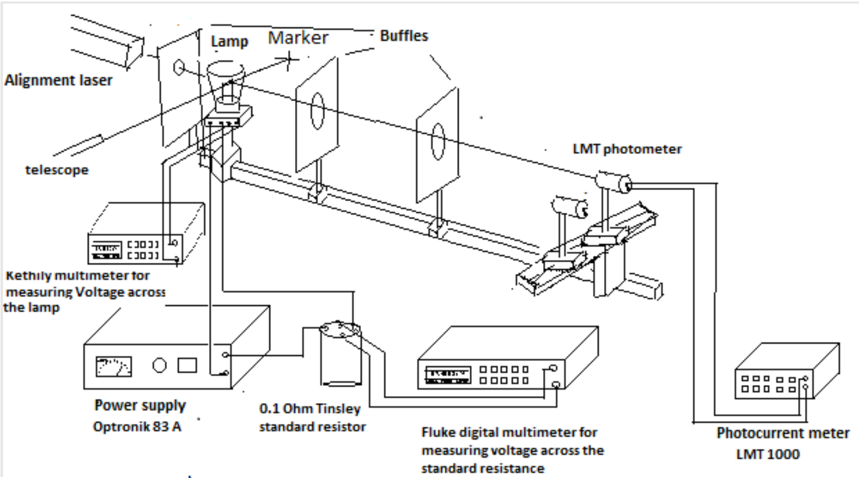


Fig. A13.1 luminous intensity measurement setup

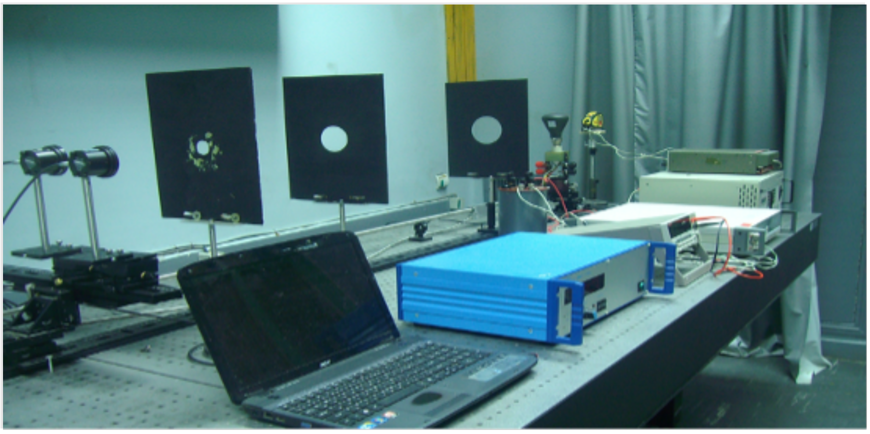


Fig. A13.2 Photometry lab in NIS - Luminous intensity measurement

4) Establishment or traceability route of primary scale:

The unit of luminous intensity, candela, at NIS is traceable to the National Physical Laboratory (NPL), maintained by a set of lamps (Osram and FEL lamps) and regularly transferred to secondary and working standards. The last connection with NPL was done in 2007 to provide group of Osram and FEL lamps calibrated for luminous intensity with a relative uncertainty ($k = 2$) of ± 0.7 %.

5) Description of calibration laboratory conditions:

The photometry calibration laboratory is 6 m x 3 m. An optical table of length 480 cm x 120 cm is located in the lab. The walls are covered with black and grey curtains. The lab is temperature-controlled. The lab temperature and humidity were monitored and recorded during calibration.

The average laboratory temperature is 22 °C ± 1 °C.

The average Humidity is 45 % ± 10 %.

6) Operating conditions of the lamps:

A special socket for the lamp E27 was purchased from LMT. The base was screwed on a tilt and rotational stage carrier, which moves along the rail axis. The base has four separate contacts, two for current supply and the other two for voltage measurements. Two electrical leads soldered to the lamp contacts, connect them to two large terminals in the base for current and voltage connection. The lamps are mounted in the base-down position with its window facing the photometer. Lamps were operated with a fixed polarity, positive potential connected to the center contact of the original lamp. The lamp was operated from the stabilized power supply of stability better than 0.02 %. The lamp was connected in series with the power supply and shunt resistor. The electrical quantity set was current. Lamp current was measured with the help of a shunt resistor (0.1 Ω) and DVM. The shunt resistor and DVM were calibrated at NIS Electricity Division.

Lamp current was ramped up slowly in around a few minutes until it reaches the specified operating value. The lamps were allowed to stabilize for minimum 20 minutes before taking measurements. This time was sufficient for both the lamp and detector to stabilize.

Geometrical alignment

The lamp filament was oriented vertically by visual comparison of the filament inclination with a plumb-line. The height of the filament was adjusted by altering its position until the middle of the filament coincided with a marker on the plumb-line. A telescope is mounted on the optical table perpendicular to optical rail so that the lamp can be seen when looking through the telescope. Using the telescope, the lamp is turned so that the area of the filament seen through the telescope is minimized. [Ref 1, 2]

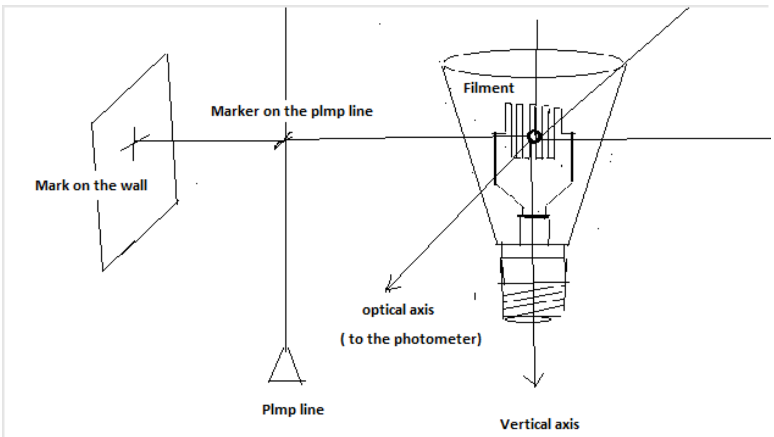


Fig. A13.3 Alignment of the lamp

Stray light

One of the most common source errors in these measurements, is stray light. The detector is very sensitive to stray light. Therefore, the lamp and detector have to be carefully baffled to obscure light from directions other than that directly fallen from the lamp. Different sized baffles between the lamp and detector were located at strategic positions, so that no light traveled from the lamp to detector other than along optical axis. One source of stray light was the lamp itself. The background of the lamp on the side away from the detector should not reflect radiation back along the optical axis. Black baffles positioned about 30 cm behind the lamp were convenient. Black cloth used to cover the detector head, which was held around the outside edges of the optical bench. An aperture (iris diaphragm) was placed near the detector (about 20 cm from the detector and opened about 2 cm diameter) to minimize the inter-reflected light. A small obscuring circular baffle, 5 mm in diameter, was mounted on the optical axis between the lamp and detector. This baffle was adjusted so that it blocked the direct beam to the detector from all parts of the lamp, but allow light from the surrounding area to reach the detector. This provided a measure of the background radiation reaching the detector from the illuminated background, from scatter of the baffle edges. The signal measured with the baffle in place was subtracted from the unblocked signal. The diaphragm closest to the photometers was the one in the shutter, which was opened to about 22 mm diameter and placed approximately 20 cm from the photometers. The uncertainty due to stray light from the measurement set-up is estimated as 0.1 %.

References

[1] *Final Report on the International Comparison of Luminous Responsivity CCPR-K3.b* R. Köhler, M. Stock, C. Garreau, Bureau International des Poids et Mesures, Pavillon de Breteuil 92312 Sèvres Cedex France, *November 2001*

[2] Final Report of the APMP Comparison of Luminous Responsivity (APMP.PR-K3.b) April 2004, J.L. Gardner, E. Atkinson M. Stock CSIRO National Measurement Laboratory

A.13.4 Uncertainty budget of Measurement

Table A13.3 Uncertainty budget for luminous intensity calibrations of transfer standards

	Uncertainty component	Type	Uncertainty / %	C_i	PD	Divisor	DoF	Relative standard uncertainty (%)
1	Calibration of the lamp	B	0.7	1	normal	2	∞	0.35
2	Random noise during transfer measurement	A	0.05	1	normal	1	∞	0.05
3	Long- term stability of standard lamps during time of calibration	B	0.08	1	rectangular	$\sqrt{3}$	∞	0.05
4	Long- term stability of the transfer lamps	B	0.2	1	rectangular	$\sqrt{3}$	∞	0.12
5	Error in electrical parameters (Current measurement-stability of power supply and error in shunt resistor)	B	0.03	6.25	rectangular	$\sqrt{3}$	∞	0.11

6	Detector alignment	A	0.1	1	normal	1	∞	0.10
7	Stray light	B	0.1	1	rectangular	$\sqrt{3}$	∞	0.06
8	Effect of temperature and humidity	A	0.05	1	normal	1	∞	0.05
9	Alignment of the lamp distance (1 mm in 3 meter)	A	0.1	2	normal	1	∞	0.20
10	Repeatability (including alignment)	A	0.4	1	normal	1	19	0.40
	Relative combined standard uncertainty							0.61
	Relative expanded uncertainty (with coverage factor (*k*) giving approximately 95 % confidence interval)							1.21

C_i: Sensitivity factor
PD: Probability Distribution
DoF: Degree of Freedom

Annex B: Changes during pre-Draft A process

B.1. Pre-Draft A1 (Verification of reported results)

As shown in 3.4, CMS/ITRI submitted the corrected data, which was based on the consideration of technical issue for their optical ruler in the second-round measurements. BSN submitted their revised uncertainty budget table, which corrected the mistake of the value for their reference standards. According to the CCPR-G2 guideline, the detail of these changes is not shown in this report.

In addition to the corrections shown above, most participant NMIs made minor editorial corrections on the report. When the pre-draft A1 was started, the pilot laboratory recommended each participant to consider having another look on their reports with some editorial comments. Furthermore, the pilot laboratory asked to provide some missing information that should be included in the measurement report. The main editorial corrections made during this stage were harmonizing significant digit, identifying effective degree of freedom, and clarification of the temperature-related parameter used for the measurement; CCT or DT.

B.2. Pre-Draft A2 (Review of uncertainty budget tables)

B.2.1 Summary

During the pre-draft A2 stage, three feedbacks were received, two of them were comments about the uncertainty budget of CMS/ITRI, and the other is a comment for NIM regarding the consistency of the uncertainty budget to the CCPR-K3.a (1999) as a link laboratory. CMS/ITRI and NIM addressed the comments with the following changes.

1) CMS slightly modified their uncertainty budget for clarification without changing total uncertainty. The participant NMIs who asked the questions were satisfied with the reply and their revised uncertainty budget.
2) NIM prepared a document that explained the detail of their uncertainty budget in this comparison and compared with the uncertainty budget used in the CCPR-K3.a (1999). The participant NMI who asked the question was satisfied with the reply. There was no modification of NIM's uncertainty budget in the pre-draft A2.

B.2.2 Revision of uncertainty budget by CMS/ITRI

Comment (1):

From the budget table of CMS/ITRI, TW, it is not quite clear how the relative combined standard uncertainty was calculated. It seems not the root-sum-square of all the standard uncertainties. Is there an explanation of how it was calculated?

Comment (2):

In the CMS's budget, I think it might be more relevant if CMS expresses the pooled value of repeatability instead of the four values being shown or indicate which one they use to get the combined value.

Reply by CMS/ITRI:

The attached is our revised uncertainty budget. I remove the list of repeatability for each lamp and leave the worst one for uncertainty calculation. The combined standard uncertainty is the root-sum-square of all the 6 standard uncertainty components.

The original uncertainty budget initially submitted from CMS/ITRI is shown in Table B2.1. For the uncertainty budget table after the pre-draft A2, see Annex A2.4.

Table B2.1 Uncertainty budget table for CMS/ITRI before the pre-draft A2

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty (%)
1	Absolute radiometer	B	200	0.13 %
2	Electrical power	B	200	0.034 %
3	Correction factor of the V(λ) filter	B	200	0.25 %
4	Effective area of the absolute radiometer	B	200	0.0252 %
5	Distance	B	200	0.012 %
6	Repeatability	A		
	CMS 1		9	0.1669 %
	CMS 2		9	0.1864 %
	CMS 3		9	0.2013 %
	CMS 4		9	0.1937 %
	Relative combined standard uncertainty		72	0.349 %
	Relative expanded uncertainty (with coverage factor (k) giving approximately 95 % confidence interval)			0.70 %

B.2.3 Discussion about the uncertainty budget by NIM

Comment:

Regarding the uncertainty component “Luminous intensity of reference standard” for NIM, the wording suggests the reference standard is a lamp, not a photometer. Is this correct? If this is their own scale, then the uncertainty in luminous intensity of the reference standard is less than that claimed in this comparison. Does this suggest that lamps used in this comparison are not of adequate quality to show their capability?

Reply by NIM:

The total uncertainty for NIM is 0.48 % (k = 2) which includes the transfer uncertainty of the pilot laboratory at last CCPR-K3.a international comparison, the current uncertainty is 0.42 % (k = 2) which does not include the transfer uncertainty of pilot laboratory.

NIM prefer to use the improved uncertainty 0.42 % (k = 2) for APMP-K3a, the details of the uncertainty budget are shown in APMP.PR-K3a- Pre-Draft A1 Annex F.

Compared with the last CCPR comparison, the uncertainties for unit realization and transfer uncertainty have some changes:

1) The uncertainty of "luminous intensity of reference standard lamp" has been changed from 0.14 % to 0.16 %, as the stability of the reference standard lamp group is decreased.
2) The transfer uncertainty has been improved from 0.18 % to 0.13 %, as the photometric measurement facility has improved at NIM.

- The power supply and electrical measurement system have been upgraded by new ones with better stability and accuracy.
- A kind of filament plane regulator has been developed which greatly improved the accuracy of lamp position adjustment;
- Reading accuracy of the photometry bench ruler was improved;
- A picoammeter was used to measure the photocurrent replacing the photometer, the precision and nonlinearity of photocurrent measurement were improved.
- Some methods are adopted to reduce the stray light and it was effectively decreased.

The luminous intensity value of NIM keeps stable since last CCPR K3a comparison. Two lamps which are being used as transferring artifacts in CCPR K3a were re-measured at this APMP.PR K3a comparison. It was confirmed that the deviation of luminous intensity of previous value and current value was within the measurement uncertainty.

B.3. Pre-Draft A3 (Review of Relative Data)

B.3.1 General

Changes happened during the pre-draft A3 process were 1) correction of measurement results and uncertainty budget table based on the review of relative data by NMISA, and 2) withdrawal of measurement results for two transfer standard lamps out of four by NIM. No non-link participant requested to remove the data of a specific lamp.

B.3.2 Report from NMISA on the corrections of the reported values

Report submitted from NMISA on the rationale of their correction of the measurement results as well as uncertainty budget are shown below.

Report on corrections made to NMISA's reported values during pre-Draft A stage of APMP.PR-K3.a

Report by:	Irma Rabe
Report checked by:	Pieter du Toit
Calibration of:	Luminous intensity standard lamps

Manufacturer:	OSRAM
Model number:	Wi41/G
Serial number:	24 (4595 PTB 09), 39 (4596 PTB 09), 42 (4597 PTB 09)
Calibration procedure:	See below

1. PROCEDURE

The luminous intensity of each lamp was determined using a partial-filtering photometer, calibrated against a silicon photodiode, which has traceability to silicon trap detectors calibrated by NPL, for absolute power responsivity at 568,2 nm (and which was interpolated to 556,1 nm using manufacturer specifications on the relative responsivity). The lamps were mounted base down with their filaments aligned perpendicularly to the optical axis. The distance between the lamp and photometer was approximately 2,7 m, as measured from the centre of the lamp filament to the front of the diffuser of the partial-filtering photometer. The optical axis was horizontal and passed through the centre of the lamp filament and the centre of the photometer diffuser. The partial-filtering photometer diffuser was aligned perpendicular to the optical axis. Baffles were used to reduce stray light. Five measurements per lamp were performed during each of the two measurement sets. The lamps were powered down, repositioned and realigned, and powered up between the different sets. The operating currents of the lamps were set to the same current values as determined during the correlated colour temperature (CCT) measurements to achieve a CCT of approximately 2856 K.

The following equation can be used to calculate the luminous intensity of a lamp [B-1]:

$$I_{\mathrm{v}} = \frac{K_{\mathrm{m}} F i r^2}{s(555) A} \qquad \text{(B.1)}$$

with

I_{v}	luminous intensity
K_{m}	maximum luminous efficacy (at 555 nm)
F	spectral mismatch correction factor of the photometer
i	photocurrent measured with the photometer
r	distance between the lamp filament and diffuser of the photometer
$s(555)$	absolute responsivity of the photometer at 555 nm
A	area of the photometer aperture

In our case, the equation was adapted to:

$$I_{\mathrm{v}} = \frac{K_{556,1} F i r^2}{s(556{,}1) A} \qquad \text{(B.2)}$$

with

I_{v}	luminous intensity
$K_{556,1}$	luminous efficacy at 556,1 nm
F	spectral mismatch correction factor of the partial-filtering photometer
i	photocurrent measured with the partial-filtering photometer
r	distance between the lamp filament and diffuser of the partial-filtering photometer

$s(556{,}1)$	absolute responsivity of the partial-filtering photometer at 556,1 nm
A	area of the partial-filtering photometer aperture

The spectral mismatch correction factor, F, was calculated using the following equation:

$$F = \frac{\int V(\lambda)S(\lambda)d\lambda}{\int s(\lambda)S(\lambda)d\lambda} \quad \text{(B.3)}$$

with

$V(\lambda)$	luminous efficacy function made relative at 556,1 nm
$S(\lambda)$	relative spectral distribution of the measured lamp
$s(\lambda)$	spectral responsivity of the partial-filtering photometer made relative at 556,1 nm

2. LIST OF CORRECTIONS AND REVISIONS

In the initial luminous intensity calculations, the value of maximum luminous efficacy, K_m, at 555 nm was used, i.e., 683 lm W^{-1}. However, the relative spectral responsivity of the partial-filtering photometer, $s(\lambda)$, was normalised at 556,1 nm (from manufacturer specifications on the relative responsivity) so the absolute responsivity was determined at 556,1 nm for the calculation in Equation (B.2). For the revised calculation, the luminous efficacy at 556,1 nm, $K_{556,1}$, was determined and used in the calculation of luminous intensity. To calculate the luminous efficacy at 556,1 nm, the $V(\lambda)$ curve (luminous efficacy function) as given in CIE 015, was interpolated to determine the value of the $V(\lambda)$ at 556,1 nm and the following equation was used:

$$K_{556,1} = K_{555}\frac{V(556{,}1)}{V(555)} \quad \text{(B.4)}$$

with

$K_{556,1}$	luminous efficacy at 556,1 nm
K_{555}	luminous efficacy at 555 nm
$V(556{,}1)$	luminous efficacy function value at 556,1 nm
$V(555)$	luminous efficacy function value at 555 nm

In the originally submitted results, the spectral mismatch factor was calculated for the relative spectral distribution of a measured luminous intensity lamp with a correlated colour temperature (CCT) of approximately 2 851 K, and at 2 851 K plus and minus the laboratory's uncertainty in CCT (± 30 K). The average of these three spectral mismatch factors was used in the calculation of luminous intensity for all three luminous intensity lamps used in the intercomparison. During the revision of the results, the spectral mismatch factor was calculated for each individual luminous intensity lamp, using the relative spectral distribution determined for the measured CCT of each respective lamp.

The absolute spectral responsivity of the partial-filtering photometer at 556,1 nm, $s(556{,}1)$, was also revised. The partial-filtering photometer was calibrated for absolute spectral responsivity at 568,2 nm. A better interpolation method, i.e., cubic spline interpolation as recommended by CIE 015, was used to determine the relative spectral responsivity of the partial-filtering photometer at 568,2 nm. The absolute responsivity at 556,1 nm, was then calculated from:

$$s(556,1) = s(568,2)\frac{s_{\mathrm{rel}}(556,1)}{s_{\mathrm{rel}}(568,2)} \quad \text{(B.5)}$$

with

$s(556,1)$	absolute spectral responsivity at 556,1 nm
$s(568,2)$	absolute spectral responsivity at 568,2 nm
$s_{\mathrm{rel}}(556,1)$	relative responsivity of the partial-filtering photometer at 556,1 nm
$s_{\mathrm{rel}}(568,2)$	relative responsivity of the partial-filtering photometer at 568,2 nm

The photocurrent measured with the partial-filtering photometer, i in Equation (B.2), was determined from the voltage measured with the partial-filtering photometer and amplifier combination, and the feedback resistance of the gain setting used on this dedicated amplifier. This value of the gain resistance used in the calculation of luminous intensity was revised.

The uncertainty of measurement calculation was revised, see Table B3.3.

3. REFERENCES

[B-1] Cromer, C., Eppeldauer, G., Hardis, J., Larason, T., Ohno, Y., & Parr, A. (1996). The NIST Detector-Based Luminous Intensity Scale. Journal of Research of the National Institute of Standards and Technology, p109-p132.

[end of the report]

Measurement results and uncertainty budget initially submitted from NMISA are shown in Table B3.1 and Table B3.2.

For the data reported after the pre-draft A3, see Annex A12.1 and A12.4.

Table B3.1 Measurement results for NIMSA before the pre-draft A3 (1st Round (December 2013))

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
"24" 4595 PTB 09	5.8240	30.258	2859	268.6
"39" 4596 PTB 09	5.8920	30.828	2864	283.8
"42" 4597 PTB 09	5.8800	30.727	2865	276.3

Table B3.2 Measurement results for NIMSA before the pre-draft A3 (2nd Round (May 2014))

Lamp No.	Current (A)	Voltage (V)	CCT (K)	Luminous Intensity (cd)
"24" 4595 PTB 09	5.8240	30.242	2841	269.0
"39" 4596 PTB 09	5.8920	30.816	2853	283.9
"42" 4597 PTB 09	5.8802	30.713	2848	274.6

Table B3.3 Uncertainty budget table for NIMSA before the pre-draft A3

	Uncertainty component	Type	Degree of Freedom	Relative standard uncertainty/ %
1	Reference standard (photometer)	B	Infinite	0.3900
2	Spectral mismatch of photometer	B	200	0.1996
3	Non-linearity of photometer	B	200	0.0500
4	Photometer temperature dependence	B	200	0.0050
5	Spatial uniformity of photometer	B	200	0.0500
6	Distance measurement	B	200	0.0092
7	Electrical measurement	B	200	0.0115
8	Lamp orientation	B	200	0.0163
9	Lamp alignment	B	200	0.0163
10	Lamp current setting stability	B	200	0.0058
11	Stray light	B	200	0.0200
12	Diffraction	B	200	0.0300
13	Repeatability	A	200	0.0100
14	Drift/ageing of lamps	B	200	0.0500
15	Aperture area	B	200	0.0500
	Relative combined standard uncertainty			0.45
	Relative expanded uncertainty (with coverage factor (*k*) giving approximately 95 % confidence interval)			0.90

B.3.3 Suggestion from NIM to withdraw the data of two lamps

We think two of our transfer standards, Wi41/G -1 and Wi41/G -27 were drifting. First, based on the initial and return measurement result and also the relative data came from the pilot laboratory. Second, the filament of the two lamps changed from the original, an arc shape appeared in the filament plane of the transfer standard Wi41/G-1, it is not a plane anymore. The filament in the transfer standard Wi41/G-27 suffered from certain oxidation (See Fig. B3.1). These changes may result in significant impacts.

As you know, NIM reported the uncertainty budget in APMP.PR-K3a-Pre-Draft A1 Annex, where the relative expanded uncertainty with approximately 95 % confidence interval is 0.42 % and a main uncertainty component is 0.16 % (relative standard uncertainty), from the luminous intensity of reference standard. If this main and systematic component is excluded from consideration, it is easy to see that the deviation of the first round to the second round of lamp Wi41/G -1 and Wi41/G -27 has been out of the uncertainty budget.

In order to make a better link to KCRV for APMP.PR-K3a comparison with smaller link uncertainty caused by the drift of the transfer standards of the link laboratory, NIM would like to query if the lamp Wi41/G -1 and Wi41/G -27 can be both taken out from future calculation. Otherwise, we suggest weighted mean method be used for data analysis of NIM data, and the weighted factor is correlated with the reciprocal of drift rates.

Wi41G - 1 Wi41G - 27

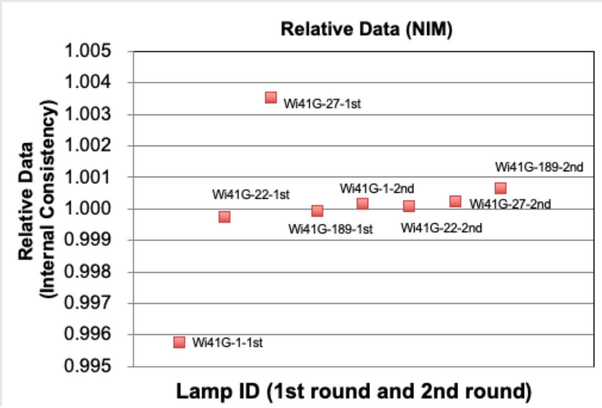
Fig. B3.1 Photo of OSRAM Wi41/G lamps

Annex C: Relative data distributed in the pre-Draft A3

C.1. National Institute of Metrology (NIM)

Table C1.1 Relative data (tabulated and graphic forms) for NIM

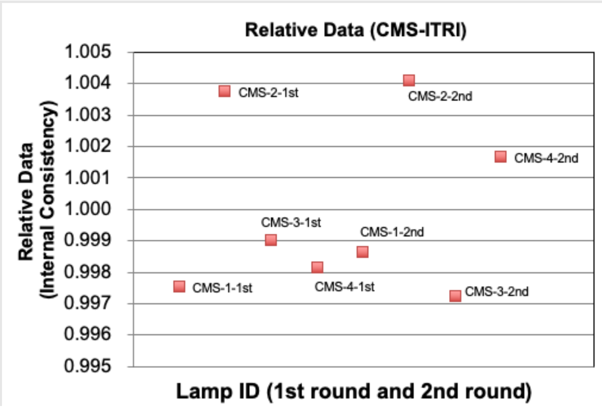
Lamp ID	Relative data
Wi41G-1-1st	0.99576
Wi41G-22-1st	0.99971
Wi41G-27-1st	1.00352
Wi41G-189-1st	0.99991
Wi41G-1-2nd	1.00014
Wi41G-22-2nd	1.00008
Wi41G-27-2nd	1.00022
Wi41G-189-2nd	1.00066



C.2. Center for Measurement Standards (CMS/ITRI)

Table C2.1 Relative data (tabulated and graphic forms) for CMS/ITRI

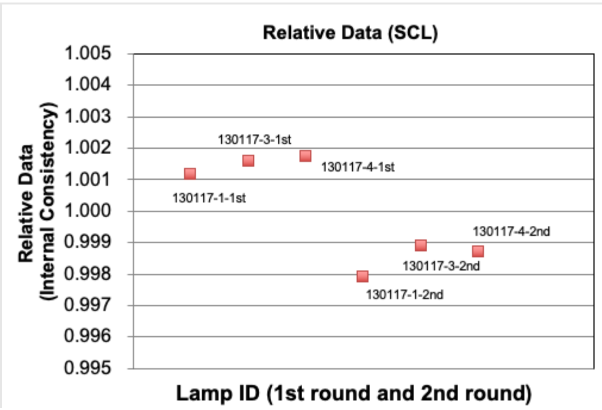
Lamp ID	Relative data
CMS-1-1st	0.99753
CMS-2-1st	1.00373
CMS-3-1st	0.99902
CMS-4-1st	0.99813
CMS-1-2nd	0.99861
CMS-2-2nd	1.00410
CMS-3-2nd	0.99722
CMS-4-2nd	1.00166



C.3. Standards and Calibration Laboratory (SCL)

Table C3.1 Relative data (tabulated and graphic forms) for SCL

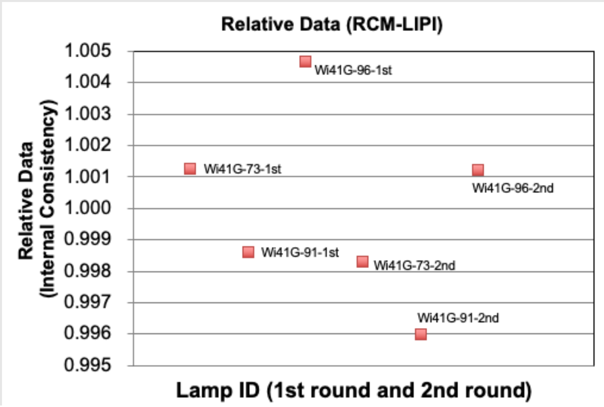
Lamp ID	Relative data
130117-1-1st	1.00115
130117-3-1st	1.00157
130117-4-1st	1.00175
130117-1-2nd	0.99791
130117-3-2nd	0.99890
130117-4-2nd	0.99872



C.4. National Standardization Agency of Indonesia (BSN)

Table C4.1 Relative data (tabulated and graphic forms) for BSN

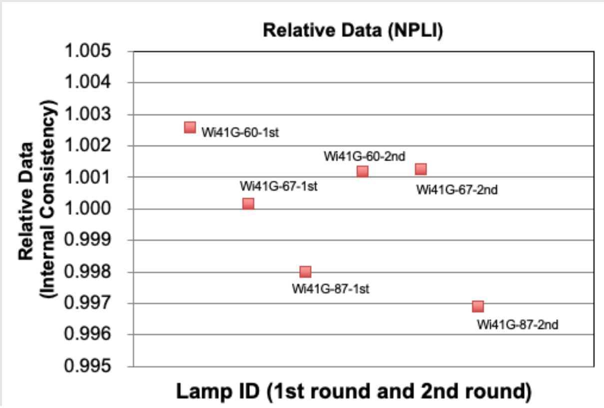
Lamp ID	Relative data
Wi41G-73-1st	1.00125
Wi41G-91-1st	0.99861
Wi41G-96-1st	1.00466
Wi41G-73-2nd	0.99828
Wi41G-91-2nd	0.99597
Wi41G-96-2nd	1.00122



C.5. National Physical Laboratory (NPLI)

Table C5.1 Relative data (tabulated and graphic forms) for NPLI

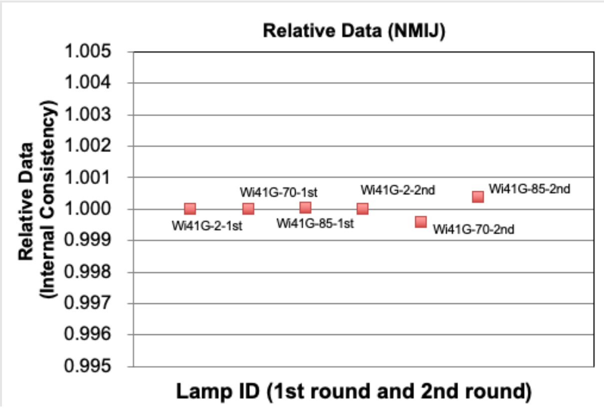
Lamp ID	Relative data
Wi41G-60-1st	1.00258
Wi41G-67-1st	1.00015
Wi41G-87-1st	0.99798
Wi41G-60-2nd	1.00115
Wi41G-67-2nd	1.00124
Wi41G-87-2nd	0.99689



C.6. National Metrology Institute of Japan (NMIJ)

Table C6.1 Relative data (tabulated and graphic forms) for NMIJ

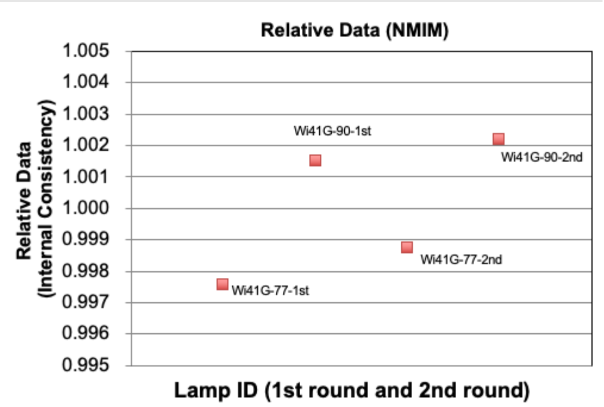
Lamp ID	Relative data
Wi41G-2-1st	1.00001
Wi41G-70-1st	0.99999
Wi41G-85-1st	1.00002
Wi41G-2-2nd	1.00001
Wi41G-70-2nd	0.99958
Wi41G-85-2nd	1.00039



C.7. National Metrology Institute of Malaysia (NMIM)

Table C7.1 Relative data (tabulated and graphic forms) for NMIM

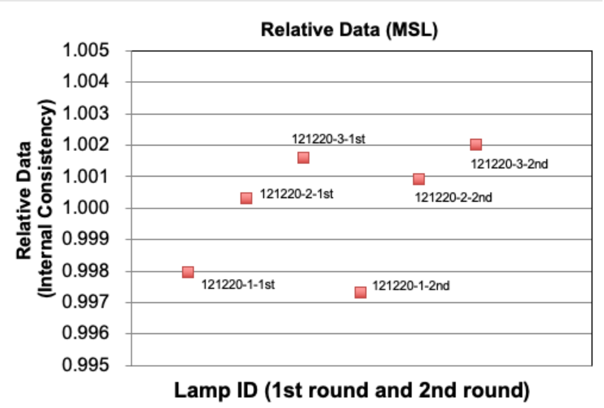
Lamp ID	Relative data
Wi41G-77-1st	0.99758
Wi41G-90-1st	1.00149
Wi41G-77-2nd	0.99874
Wi41G-90-2nd	1.00219



C.8. Measurement Standards Laboratory (MSL)

Table C8.1 Relative data (tabulated and graphic forms) for MSL

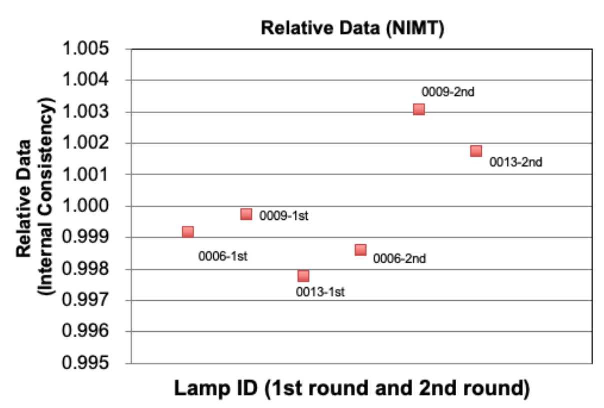
Lamp ID	Relative data
121220-1-1st	0.99793
121220-2-1st	1.00029
121220-3-1st	1.00159
121220-1-2nd	0.99730
121220-2-2nd	1.00090
121220-3-2nd	1.00198



C.9. National Institute of Metrology (NIMT)

Table C9.1 Relative data (tabulated and graphic forms) for NIMT

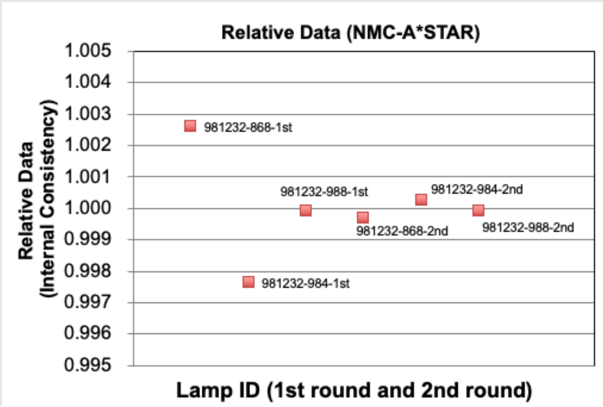
Lamp ID	Relative data
0006-1st	0.99914
0009-1st	0.99972
0013-1st	0.99777
0006-2nd	0.99859
0009-2nd	1.00305
0013-2nd	1.00173



C.10. National Metrology Centre (NMC-A*STAR)

Table C10.1 Relative data (tabulated and graphic forms) for NMC-A*STAR

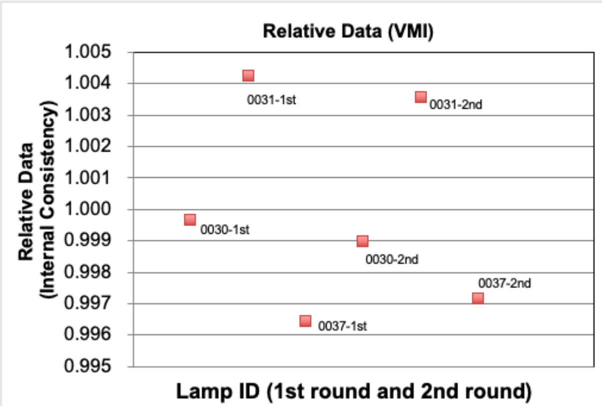
Lamp ID	Relative data
981232-868-1st	1.00259
981232-984-1st	0.99763
981232-988-1st	0.99992
981232-868-2nd	0.99970
981232-984-2nd	1.00026
981232-988-2nd	0.99992



C.11. Vietnam Metrology Institute (VMI)

Table C11.1 Relative data (tabulated and graphic forms) for SCL

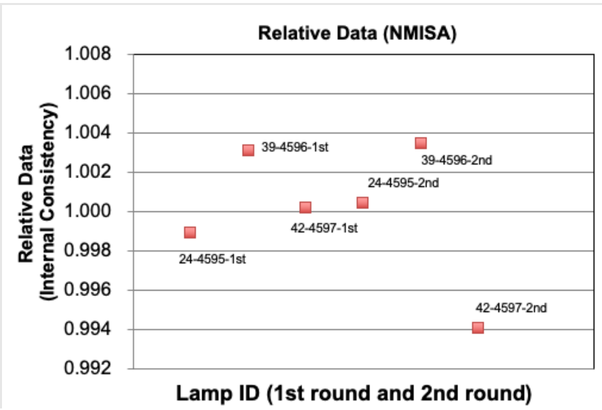
Lamp ID	Relative data
0030-1st	0.99967
0031-1st	1.00423
0037-1st	0.99644
0030-2nd	0.99897
0031-2nd	1.00354
0037-2nd	0.99715



C.12. National Metrology Institute of South Africa (NMISA)

Table C12.1 Relative data (tabulated and graphic forms) for NMISA

Lamp ID	Relative data
24-4595-1st	0.99891
39-4596-1st	1.00306
42-4597-1st	1.00018
24-4595-2nd	1.00040
39-4596-2nd	1.00342
42-4597-2nd	0.99403

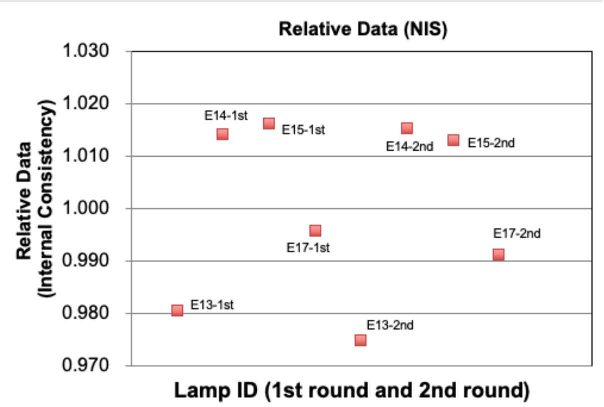


Note: NMISA's measurement results were revised during the pre-draft A3 after the relative data was appeared.

C.13. National Institute for Standards (NIS)

Table C13.1 Relative data (tabulated and graphic forms) for NIS

Lamp ID	Relative data
E13-1st	0.98036
E14-1st	1.01401
E15-1st	1.01616
E17-1st	0.99575
E13-2nd	0.97462
E14-2nd	1.01509
E15-2nd	1.01291
E17-2nd	0.99109



Annex D: Statement on the measurement results from CMS/ITRI

CMS/ITRI's explanations of the results of APMP.PR-K3.a (Submitted on 23 February 2023)

It was found in the Draft A of APMP.PR-K3.a released in the end of 2022 that the data of CMS/ITRI are higher than the ones of other labs.

The measurement for this comparison was conducted in 2013 and 2014. We had found the optical ruler used for the comparison malfunctioned in early 2015. After the optical ruler was repaired, the measurement data of this system are all lower than the data before repair. It could be possible that the optical ruler used in the comparison already showed some signs of malfunction in 2013, resulting in higher comparison data. However, due to the lack of sufficient data before the repair of the optical ruler, there is not enough information to evaluate the effect of instrument deviation on the measurement data in 2013 and 2014.