CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Arnold Gaertner[1], Éric Côté[1], Joaquin Campos[2], Gaël Obein[3], Peter Blattner[4], Reto Schafer[4], Liu Hui[5], Jiang Xiaomei[5], Cameron Miller[6], Yuqin Zong[6], Errol Atkinson[7], Erik Thorvaldson[7], Kenichi Kinoshita[8], Rheinhardt Sieberhagen[9], Irma Rabe[9], Teresa Goodman[10], Barry Scott[10], Armin Sperling[11], Detlef Lindner[11], Boris Khlevnoy[12], Evgeniy Ivashin[12].

1 National Research Council Canada (NRC), Canada (pilot laboratory)
2 Instituto de Optica (IO-CSIC), Spain
3 Laboratoire Commun de Métrologie (LNE-CNAM), France
4 Federal Institute of Metrology (METAS), Switzerland
5 National Institute of Metrology (NIM), China
6 National Institute of Standards and Metrology (NIST), United States of America
7 National Measurement Institute, Australia (NMIA), Australia
8 National Metrology Institute of Japan (NMIJ, AIST), Japan
9 National Metrology Institute of South Africa (NMISA), South Africa
10 National Physical Laboratory (NPL), United Kingdom
11 Physikalisch-Technische Bundesanstalt (PTB), Germany
12 All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI), Russia

Contents

1. Introduction

1.1 The metrological equivalence of national measurement standards will be determined by a set of key comparisons chosen and organized by the Consultative Committees of the CIPM working closely with the Regional Metrology Organizations (RMOs).

1.2 At the 14th meeting of the Consultative Committee for Photometry and Radiometry (CCPR) held on 1997-June-10 and 11, several key comparisons in the field of optical radiation metrology were identified. In particular, it decided that luminous intensity/responsivity be considered a Key Comparison (KC) and that the comparisons being piloted by PTB (K3.a Luminous Intensity of lamps) and the BIPM (K3.b Luminous Responsivity of photometers) at that time be treated as Key Comparisons. These first KCs of luminous intensity/responsivity were completed in 1999 [1]. At the 20th meeting of the CCPR (2009-September-17, 18), it was decided that a second round of key comparison CCPR-K3 be commenced [2]. The CCPR approved "that for this next round there will be only one CCPR-K3 comparison, called luminous intensity, and the details of the comparison (use of lamps or photometers) should be decided by the task group carrying out the comparison. The task group will be established by the WG-KC and its proposal of comparison artifacts shall be submitted to CCPR for approval."[1] The National Research Council of Canada (NRC) was chosen to pilot this comparison, with the intention that measurements would start in 2012.

1.3 The technical protocol was drawn up by the eight-member Task Group (TG) of the participants of the CCPR-K3.2014 key comparison (see Section 2.3.), approved by all the participants, and approved by the WG-KC.

1.4 This is the Final Report of the CCPR-K3.2014 Key Comparison. Draft A was reviewed and approved by the participants in 2020-October. The draft B report was reviewed by CCPR WG-KC from 2020-October to 2021-April, including one revision. The Draft B-2 was approved by the CCPR WG-KC on 2021-April-02 and by the CCPR on 2021-November-30.

1.5 This report describes the comparison organisation (Section 2), the measurement methods and uncertainties achieved at all the participants and at the pilot (Sections 3 and 4), and the method for analysis and the results of the comparison according to this method (Section 4). It includes a comparison of the results of this comparison with the 1999 comparison [1] (Section 5). Section 6 presents a summary of the comparison.

[1] WG-KC = CCPR Working Group on Key Comparisons

2. Organization

2.1. Participants, selection

2.1.1 The invitation to participate in this comparison was prepared by the pilot laboratory and the WG-KC, and then sent to all CCPR members by Michael Stock, Executive Secretary of the CCPR.

2.1.2 The selection process for the participants was guided by the following criteria [4]:

1. The participant must be a member of CCPR.
2. The participant must be willing to serve as a link laboratory to their RMO.
3. The participant must have an independent realization of the unit or scale of the comparison quantity.
4. The participant's measurement capability of the comparison quantity, over the full range of the comparison (e.g., full spectral range), must be listed in the CMC table published at the time of the call for participants.

2.1.3 Since the number of applications exceeded the maximum of 12, the RMO Groups were requested by the pilot to select the maximum number of participants in accordance with the following Table One [4]:

Table One		
RMO Group	**RMO Group Members**	**Maximum Number of Participants**
Group 1	EURAMET+COOMET	6
Group 2	APMP+AFRIMETS	4
Group 3	SIM	2

2.2. Participants, contact information

The final 12 participants selected are given in the following Table Two.

Table Two				
NMI			**NMI Contact**	
NMI	**Address**	**RMO**	**Name**	**Address**
NMISA	National Metrology Institute of South Africa Building 5, CSIR Campus Meiring Naudé Road, Brummeria, 0184 Pretoria, South Africa	AFRIMETS	Sieberhagen, Dr. Rheinhardt	TEL: +27 12 841 3618 EMAIL: rsieberhagen@nmisa.org
NIM	National Institute of Metrology, China No. 18, Bei San Huan Dong Lu Chaoyang Dist Beijing, P.R.China 100029	APMP	Hui, Mrs. Liu	TEL: 86-10-64524830 EMAIL: liuhui@nim.ac.cn

NMIA	National Measurement Institute, Australia 36 Bradfield Rd, West Lindfield, NSW 2070, AUSTRALIA	APMP	Manson, Dr. Peter	TEL: +61 2 8467 3858 EMAIL: peter.manson@measurement.gov.au
NMIJ	Optical Radiation Section Photometry and Radiometry Division National Metrology Institute of Japan (NMIJ) National Institute of Advanced Industrial Science and Technology (AIST) Tsukuba Central 3-1, 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563 Japan	APMP	Kinoshita, Dr. Kenichi	TEL: +81 29 861 4082 EMAIL: kenichi.kinoshita@aist.go.jp
IO-CSIC	Instituto de Optica (IO, CSIC) Serrano, 144. 28006 Madrid, Spain	EURAMET	Pons, Dr. Alicia Campos, Dr. Joaquin	TEL: +34 915618806 EMAIL: apons@io.cfmac.csic.es TEL: +34 915616800 EMAIL: joaquin.campos@csic.es
LNE-CNAM	LNE-CNAM Laboratoire Commun de Métrologie (LCM) 61, rue du Landy 93210 La Plaine Saint Denis, France	EURAMET	Obein, Dr. Gaël	TEL: +33 1 58 80 87 88 EMAIL: gael.obein@lecnam.net
METAS	Federal Institute of Metrology METAS Lindenweg 50 CH-3084 Wabern, Switzerland	EURAMET	Blattner, Dr. Peter	TEL: +41 58 387 03 40 EMAIL: peter.blattner@metas.ch
NPL	National Physical Laboratory Hampton Road Teddington, Middlesex TW11 0LW United Kingdom	EURAMET	Goodman, Ms Teresa	TEL: +44 (0)20 8943 6813 EMAIL: teresa.goodman@npl.co.uk
PTB	Physikalisch-Technische Bundesanstalt Bundesallee 100 38116 Braunschweig, Germany	EURAMET	Sperling, Dr. Armin	TEL: +49 531 592 4120 EMAIL: armin.sperling@ptb.de
VNIIOFI	All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI) 46 Ozernaya Str. 119361 Moscow, RUSSIA	COOMET	Khlevnoy, Dr. Boris	TEL: +7 (495) 437-29-88 EMAIL: Khlevnoy-m4@vniiofi.ru
NIST	National Institute of Standards and Technology 100 Bureau Drive, MS 8442 Gaithersburg, MD 20899 USA	SIM	Miller, Dr. Cameron	TEL: +1 301-975-4713 EMAIL: c.miller@nist.gov
NRC	National Research Council of Canada NRC Metrology 1200 Montreal Road, Building M36 Ottawa, Ontario, Canada K1A 0R6	SIM	Gaertner, Dr. Arnold	TEL: +1 613-993-9344 EMAIL: arnold.gaertner@nrc-cnrc.gc.ca

2.3. Task Group, selection

The Chair of the WG-KC requested that a subset of the 12 participants be appointed to serve on the Task Group (TG). The following eight NMIs requested to serve on the TG and were appointed by the Chair of the WG-KC:

METAS	Federal Office of Metrology, Switzerland
NIM	National Institute of Metrology, China
NIST	National Institute of Standards and Technology, USA
NMIA	National Measurement Institute, Australia
NMIJ	National Metrology Institute of Japan
NPL	National Physical Laboratory, UK
NRC	National Research Council of Canada, pilot
PTB	Physikalisch-Technische Bundesanstalt, Germany

2.4. Task Group, duties

2.4.1 Decide upon the type of artifact (lamps or photometers), and obtain CCPR approval.
2.4.2 Draft the technical protocol for the comparison.

2.5. Comparison artifacts, selection

2.5.1 Type of artifact: In response to the Call for Participants, eight of the participants had indicated a preference for standard lamps as the comparison artifact, two of the participants had indicated a preference for photometers as the comparison artifact, and two of the participants had indicated that they had no preference. The TG discussed the suitability of photometers and lamps to represent a key comparison of luminous intensity. After some (email) discussions, the TG selected standard lamps to be the comparison artifact. This decision, together with a summary report of the discussions, was submitted to the full CCPR for their approval, which was subsequently received.

2.5.2 Type of lamp: The pilot undertook a survey of all twelve participants in the comparison to determine the number and type of lamps that the participants wished to use for the comparison. Based upon the responses to this survey of the CCPR-K3.2014 participants, the comparison included both the Osram Wi41/G lamp and the NPL/Polaron Heavy Current LIS incandescent lamp. The minimum set of any traveling standards used for this comparison was a group of four lamps, with a set of six lamps recommended.

2.5.3 Type of comparison: Because of the fragile nature of the incandescent lamps, the comparison was organised as a star comparison. Each participant was required to supply their own comparison artifacts. Any individual lamp was measured by the pilot and by one participating NMI, only. The participants were requested to measure each travelling standard on at least two occasions and the pilot was also asked to make measurements on two occasions to obtain some information about the lamp stability.

For the comparison, the measurement sequence NMI – Pilot – NMI was taken to achieve the comparison results. Due to multiple measurements with a group of at least four lamps for each participant, it was expected that the uncertainties due to the comparison itself could be reduced by averaging.

2.6. Comparison measurement and analysis components

2.6.1 Pilot laboratory measurement. The detailed information concerning the measurements at the pilot laboratory has been presented in the Technical Protocol for the comparison. It was the intent of the pilot laboratory to measure all lamps from all participants under as identical conditions as possible. To this end, the measurements at the pilot did not commence until all NMI travelling standard lamps had been received at the pilot laboratory, and all lamps were then measured sequentially using the same measurement set-up, over a time period of approximately 2 months. The NMI lamps were measured upon at least two occasions for all NMIs and several lamp sets were measured three times.

The quantity compared using this setup was the photometer signal produced by the optical radiation of each lamp. This procedure does not compare the lamps to any photometric scale of the pilot laboratory, so that the lamps from the pilot NMI may be considered on an equal basis to all NMI participants. Since near-identical measurement conditions were used for each lamp, the photometer signal gives a direct comparison of all NMI lamps. Two photometers were used, sequentially at each measurement, to provide a measurement and equipment check. The measurement results from the two photometers over the two-month time period also provided information concerning the stability of the comparison reference scale. Additional information concerning the stability of this scale was determined from extra repeat measurement of the pilot lamps, and the repeat measurements of the NMI lamps also gave an indication of the scale stability.

2.6.2 Comparison analysis: The fundamental outcomes of a key comparison are the Key Comparison Reference Value (KCRV), the unilateral Degrees of Equivalence (DOEs) between each NMI and the KCRV, and the bilateral DOEs between pairs of NMIs.

The measurement procedure presented above results in a photometer responsivity $R_{i,j,m}$ in units of (cd/V) for each measurement. In this symbol, *i* is the NMI number (*i*=1 to 12), *j* is the NMI lamp number (*j*=1 to number of lamps submitted by the NMI), and *m* is the measurement number of that lamp at the pilot (*m*=1 to number of times the lamp was measured at the pilot laboratory). The candela values are the values for each lamp as obtained from the measurements submitted by the NMIs.

An average (weighted mean) value R_i is determined for each NMI. This ensures that each NMI is treated equitably and that the results do not depend upon the number of lamps submitted by the NMI, nor the number of times the lamps were measured at the pilot laboratory. However, the uncertainties associated with the final R_i for each NMI will depend upon both the number of lamps and the number of repeat measurements since the uncorrelated (random) aspects will be affected.

The KCRV is then determined from these 12 values of R_i. In this comparison, the luminous intensity scale of one of the NMIs (NMISA) was not their own independent realization. Consequently, a tentative KCRV was determined from the remaining 11 NMIs. The DOEs can be determined for all 12 participants. The KCRV determined from the R_i is the responsivity R_{KCRV} (cd/V) of the pilot photometer as determined by the measurement of a *virtual* KCRV Luminous Intensity lamp measured under the same conditions as the NMI lamps.

The uncertainties in the determination of this KCRV are based upon the combination of three basic uncertainties applied to the $R_{i,j}$ measurements of each lamp: (1) the uncertainties in the luminous intensity calibration of each NMI travelling standard as determined from the measurements of each NMI, (2) the uncertainties of the comparison measurements made at the pilot laboratory, and (3) an estimate of each lamp's repeatability as determined from the measurements at the pilot laboratory. These uncertainties are combined to produce the uncertainties in the weighted mean R_i for each participant.

The determination of the initial tentative KCRV for this comparison was made according to the CCPR guidelines [6], using only the data for the 11 NMIs as indicated above. It is based upon a weighted mean with 'cut-off'. The weights are determined based upon the NMI reported uncertainties adjusted by the cut-off, combined with the transfer uncertainty of the comparison and the uncertainty caused by the estimated lamp reproducibility observed during the measurements at the pilot lab. The cut-off value for the NMI uncertainty is 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.

This initial KCRV was then tested for statistical consistency with the measurement results using two criteria [6]: testing for statistical 'outliers', and testing for statistical indications of under-estimated uncertainties.

As indicated in the CCPR-G2 guidelines [6], Pre-Draft-A Process 4, an 'obvious outlier' was defined as participant results whose R_i deviated from the KCRV by more than 3 times its associated expanded (k=2) uncertainty. There were no 'obvious outlier' participants.

The CCPR-G2 guidelines [6] defined the Chi-Square (α=0.05) test as the statistical indication of under-estimated uncertainties. This test failed for the measurement data. It was observed that a large contribution to the Chi-Square (observed) for the measurements was due to the results from one participant, whose contribution to the Chi-square (observed) was more than one-half the total. In addition, although not an outlier, their R_i deviation from the KCRV was close to 3 times its' associated expanded (k=2) uncertainty. The comparison participants agreed that the results from this NMI would not be used to determine the KCRV, although the DOE for their results would be determined.

A new tentative KCRV was then calculated from the results of the remaining 10 participants and the statistical tests were re-applied. The Chi-square (observed) test again failed and the Mandel-Paule method was applied as suggested in the CCPR-G2 guidelines [6]. The additional uncertainty required to enable the Chi-square (observed) to pass the test was determined to be reasonable and the participants agreed to use this procedure to determine the KCRV for this comparison.

After the publication of Draft A v1.0, LNE-CNAM pointed out that the results for their transfer lamps deviated much farther from the KCRV than could be expected based upon their previous experience and measurements. It was noted that their results were for the participant identified above with R_i deviation from the KCRV close to 3 times its' associated expanded (k=2) uncertainty. It was also noted that for the shipment of lamps from LNE-CNAM, two lamps of the Polaron-type were received broken at NRC, and that one of the Osram-type lamps indicated significant changes when re-measured at LNE-CNAM after the pilot measurements, indicating that the entire shipment of their lamps had experienced a severe shock during the shipment from LNE-CNAM to the pilot. They considered it highly likely that the remaining 3 lamps would have suffered a short-term instability that would not have been noticed during the comparison measurement sequence, and requested that the results for their lamps be withdrawn from the comparison. This was accepted by the participants. This request did not affect the calculations for the KCRV or the DOE, since, as discussed above, the results from LNE-CNAM were considered 'outlier' data and not included in these calculations.

3. Comparison Procedures and Timetable

3.1. Comparison Protocol

The protocol was approved by the comparison participants on 2013-October-25 and submitted to the CCPR WG-KC for their approval. After some minor edits, the protocol was approved by the CCPR WG-KC on 2014-January-14. This was then submitted to the BIPM KCDB Coordinator and registered on 2014-January-17.

3.2. Lamp Shipment to Pilot

The first lamps were received at NRC on 2014-March-13 and the last set of lamps was received on 2014-August-26. The lamps were hand-carried by four NMIs and shipped by seven NMIs. All lamps were checked visually and electrically for electric continuity of the filaments. In the shipment of lamps from LNE-CNAM, two lamps of the Polaron-type were received broken at NRC. These lamps were attached to heavy sockets that had broken loose from their shipping mounting and the lamps had broken at the glass to metal joint of the lamp base. We received a total of 56 Osram-type lamps and 6 Polaron-type (not including the broken lamps) lamps from the 11 NMIs that delivered lamps to NRC. Together with the 6 lamps from the pilot that did not travel, the total number of lamps received was 62 Osram-type lamps and 6 Polaron-type (not including the broken lamps) lamps. A list of the lamps received is given in the following Table Three. The column labelled 'Final' is explained in Section 3.7.

Table Three						
NMI	**Number of Lamps**					
	Osram	**Polaron**	**Final**	**Transportation**	**Receipt**	**Returned**
NMISA	4	0	4/0	Ship	2014-Aug-26	2015-Jun-19
NIM	6	0	5/0	Hand Carry	2014-Mar-19	2015-Apr-16
NMIA	6	0	5/0	Ship	2014-Mar-18	2015-Feb-19
NMIJ	6	0	5/0	Ship	2014-Mar-21	2015-Jan-26
VNIIOFI	6	0	6/0	Ship	2014-Apr-23	2015-Feb-19
IO-CSIC	4	2[1]	4/1	Ship	2014-Mar-21	2015-Feb-27
LNE-CNAM	3[2]	3[2]	0[2]	Ship/Hand Carry	2014-Apr-10	2015-Apr-24
METAS	6	0	6/0	Ship	2014-Mar-13/19	2015-Feb-12/20
NPL	2	3	2/3	Hand Carry	2014-May-05	2015-Jul-30
PTB	6	0	6/0	Hand Carry	2014-Apr-14	2015-Jun-01
NIST	7	0	6/0	Hand Carry	2014-Apr-16	2015-Mar-06
NRC	6	0	6/0	No travel		
Total	62	8	55/4			

[1] One of the Polaron lamps from IO-CSIC failed during measurements at the Pilot lab.

[2] Two of the Polaron lamps shipped from LNE-CNAM were received broken at the Pilot lab. As a result the remaining lamps were hand carried by LNE-CNAM for the return to LNE-CNAM. Upon their return measurements, they observed a large change in one of the Osram lamps and asked to have it removed from the comparison. After the publication for Draft A v1.0 it was agreed to remove all the LNE-CNAM lamps from the comparison. See Section 2.6.2.

3.3. Lamp Measurement at Pilot

All the lamps were measured from 2014-November to 2015-January. All the Osram-type lamps were measured first, at least two times for each lamp, and then all the Polaron-type lamps were measured, also at least two times per lamp. One Polaron-type lamp from IO-CSIC failed during the measurements. On 2015-February-04 the participating NMIs were invited to pick-up, or have shipped, their lamps for their return (round #2) measurements. The first set of lamps was shipped from NRC on 2015-January-26 and the last set of lamps was picked-up from NRC on 2015-July-30.

3.4. Lamp Re-measurement by Participants and Report of Results

All participants re-measured their lamps (Round #2) and sent their measurement results, together with the measurement facility information, scale traceability and uncertainty budget to the Pilot by 2015-November-30. As a result of their return measurements, LNE-CNAM observed a large change in one of their Osram lamps and requested that it be removed from the comparison (see Appendix A). This was approved by all participants by 2018-October-15.

The NMI submissions concerning their measurement facility information, scale traceability and uncertainty budgets are presented in Appendix A. The uncertainty budgets given in Appendix A may contain the additional information requested as a result of the Pre-Draft-A Process 2 review of uncertainty budgets (see section 3.6 below) by all NMIs.

3.5. Pre-Draft-A Process 1: Verification of Reported Results

The Pilot assembled the data received from each participant and sent to each participant, individually, their reported values as received by the Pilot, for their verification. With some minor modifications, the results received and used by the pilot were confirmed by 2016-February-09.

3.6. Pre-Draft-A Process 2: Review of Uncertainty Budgets

The pilot distributed to all the participants the uncertainty budgets of all the participants to allow them to review all the uncertainty budgets and request further information if deemed necessary. Comments were sent to the pilot who then assembled all the comments and forwarded the comments anonymously to the participant being asked and copied to all participants. The comments received requested more information from many of the participants. Replies were received from the participants involved, assembled and reported to all participants, who were then given a further opportunity to respond. During this process the participants agreed to the request of one participant (VNIIOFI) to change their reported luminous intensity values as a result of an evaluation of their uncertainty budget. The revised VNIIOFI luminous intensity values and uncertainties are those given in Appendix A.

The results of this PDA Process 2 are presented in Appendix B. This contains both the review comments (shown in black type) and the responses received from the NMIs (shown in red type). It also includes the reason for the changes in VNIIOFI luminous intensity and uncertainty values. PDA Process 2 was completed by 2016-July-11.

3.7. *Pre-Draft-A Process 3: Review of Relative Data*

The pilot lab prepared the "Relative Data" of each participant, which are the data reduced to show only the stability of transfer standards for each participant before (Round #1) and after travel (Round #2) and the internal consistency of all the transfer standards measured at each participant lab. The "Relative Data" for all participants was distributed to all participants without identifying any of the participants.

As a response to this data, there were three requests to remove a lamp from the comparison, one request to change the reported Luminous Intensity of a lamp, and one request to use only data from the first set (Round #1) of measurements by the NMI.

1. NMIJ requested removal of their lamp #69 due to the large change in value between their Round #1 and Round #2 measurements.
2. NMIA requested removal of their lamp S14 due to the large change in value between their Round #1 and Round #2 measurements.
3. After some discussion among the participants, NIM requested removal of their lamp G-1071 due to the large difference in the relative value of this lamp between the Pilot and NIM. It was concluded that this difference was due to a difference in the construction of this lamp from their other lamps that caused the measurement set-ups at the two laboratories (Pilot and NIM) to produce different results.
4. IO-CSIC requested a change in the Luminous Intensity value given to their lamp A454 for the Round #2 measurements. They traced this to be caused by the use of the incorrect value for the resistance of their standard resistor used to measure the lamp current (see Appendix A).
5. NPL compared the relative data and their repeat (R#1, R#2) measurements and concluded that 2 lamps (Wotan lamps 877 and 890) had changed after the pilot measurements. Thus the R#1 data could still be used, but the R#2 data removed (see Appendix A).

After some discussion, these changes were accepted by all the participants (2017-February-09). This explains the values in the 'Number of Lamps/Final' column in Table Three above. The values for LNE-CNAM are explained in Section 2.6.2 above.

3.8. *Pre-Draft-A Process 4: Identification of Outliers and Consistency Check*

3.8.1 Pre-Draft-A Process 4: Identification of outliers:

A tentative KCRV was calculated by the pilot using the procedure described above in Section 2.6.2. There were no 'obvious outliers', as pre-defined in the CCPR-G2 Guideline [6], whose average R_i deviated from the tentative KCRV by as much as 6 times (k=1) the associated uncertainty for R_i.

3.8.2 Pre-Draft-A Process 4: Consistency check:

The consistency check of the data with the initial tentative weighted mean KCRV, using the Chi-square (α=0.05) test defined in the CCPR-G2 Guideline [6], resulted in $\chi^2_{obs} \approx 45.4$. This was larger than the $\chi^2_{0.05}(\nu = 10) \approx 18.3$ consistency check indicated in the example in Appendix B of the CCPR-G2 Guideline [6]. Since the data fails this Chi-square test, the Guideline then suggests the use of the Mandel-Paule method, applying an additional "inter-laboratory variance" s^2 to all the participant uncertainties that will force the data set to pass the Chi-square test. However, it was noted that more than one-half of this χ^2_{obs} was due to the results of the measurements on the lamps from one NMI. It was also noted that the measurements of these particular lamps showed a deviation from the tentative KCRV that were close to the 6 times (k=1) their associated uncertainty for R_i.

Considering the possibility of removing this data from the calculation of the KCRV, the data was reanalyzed for a tentative KCRV based upon the remaining 10-participant data. This resulted in $\chi^2_{obs} \approx 18.3.$, which is only slightly higher than the $\chi^2_{0.05}(\nu = 09) \approx 16.9$ given in the table in the example Appendix B of the CCPR-G2 Guideline [6].

The pilot then conveyed this data to the participants (2019-March-11), and suggested that the comparison KCRV be based upon the measurements of the 10 participants whose data resulted in the χ^2_{obs} close to the CCPR-G2 guideline [6]. Replies were received from 4 of the participants, all of whom approved the determination of the KCRV from the data of the remaining 10 participants. Several replies recommended, noting the requirement of the CCPR-G2 guideline [6], that since the χ^2_{obs} was still higher than 16.9, that the Mandel-Paule method be applied to reduce the χ^2_{obs} to the $\chi^2_{0.05}(\nu = 09) \approx 16.9$ given in the table in the example Appendix B of the CCPR-G2 Guideline [6].

The pilot then performed the analysis to include the Mandel-Paule uncertainty. It was determined that the additional uncertainty required to reduce the χ^2_{obs}, from approximately 18.3 to approximately 16.9, was small, approximately 0.06%, and that the changes in the KCRV and the unilateral degrees of equivalence were also small, approximately 0.0014%. This uncertainty could be explained as an adjustment due to ‘uncertainties’ in calculating the uncertainties. The pilot then proposed that the data analysis for the Draft A comparison report would include the Mandel-Paule adjustment of the uncertainties of the comparison. The participants agreed (2019-May-24) to this procedure to determine the KCRV and DOEs for this comparison.

3.8.3 Pre-Draft-A Process 4: Inconsistent Data Issues:

At this point it can be noted that the inconsistent data were from the measurements of the lamps submitted by LNE-CNAM. As indicated above in Section 3.2, two of the Polaron lamps shipped from LNE-CNAM were received broken at the Pilot laboratory. In addition, as indicated above in Section 3.4, LNE-CNAM observed, upon their return measurements, a large change in one of their Osram lamps between their pre-shipment and after return measurements, and requested that this lamp be removed from the comparison.

The return measurements at LNE-CNAM for the remaining 3 lamps did not indicate a change in these lamps larger than they would expect from the uncertainties in their measurements. Consequently, this comparison cannot choose between an actual difference in the luminous intensity scale at LNE-CNAM with respect to the KCRV, and the possibility that the lamps were damaged during their transit to the pilot laboratory and subsequently ‘annealed’ during the measurements performed at the pilot and then at LNE-CNAM upon their return, which was done by hand-carrying the lamps.

3.9. Draft A

3.9.1 Draft A v1.0

Draft A v1.0 was prepared and sent on 2019-July-24 to all participants for review. As a results of comments received the next version of Draft A was prepared.

3.9.2 Draft A v2.0

Draft A v2.0 was prepared as described below and sent on 2020-January-09 to all participants for their review.

3.9.2.1 Removal of LNE-CNAM results:

As discussed in Section 2.6.2 above, after the publication of Draft A v1.0, LNE-CNAM pointed out that the results for their transfer lamps deviated much farther from the KCRV than could be expected based upon their previous experience and measurements. Noting the shock that their shipment of lamps had sustained upon shipment to the pilot, causing the breakage of some lamps, they requested that the results for all their lamps be removed from the comparison. This was agreed to by the participants. This request did not affect the calculations for the KCRV or the DOE, since, as discussed above, the results from LNE-CNAM were considered 'outlier' data and not included in these calculations.

3.9.2.2 Adjustment of Weighting Factors used for Weighted Means of Participant Data:

Participant measurement data is combined at two stages: i) the combination of Round #1 and Round #2 values for each lamp, and ii) the combination of the results for all lamps used by a participant into a final value for the participant. The weights used in Draft A v1.0 for each of these combinations was the usual statistical inverse square of the (absolute) uncertainties of the luminous intensities. It was noted that this caused an issue with the combination of results of all lamps for participants that used both the Osram-type lamps and the Polaron-type lamps. If the lamps all have the same fractional luminous intensity uncertainties, but quite different luminous intensities, the weights for the higher intensity (Type Polaron) lamps are considerably smaller than the weights for the Osram-type lamps if absolute uncertainties are used. It was requested that fractional uncertainties be used for these calculations in order to provide a more equal weighting of all lamps used by the participant. This will have an almost negligible effect for participants that only sent one type of lamp, but will affect those that sent both types of lamps. For Draft A v2.0, fractional uncertainties are used for the combination of the results for all lamps used by a participant.

3.9.2.3 Uncertainty Analysis:

The uncertainty analysis, presented in Section 4, combines the many uncertainty components of the participant and pilot measurements. Concern was expressed that the use of the terms Type A, Type B, uncorrelated and correlated were inconsistently and incorrectly applied by both the participants and the pilot in the uncertainty analysis. The explanation and analysis in Section 4 has been reworked to provide more clarity in the procedures used in the preparation of this report. In particular, the use of the terms Type A and Type B has been avoided since they describe the origins/evaluations of uncertainties, whereas the combination of uncertainties requires the use of the correlations or non-correlations between variables. The predominant changes in calculations were made in the combination of participant uncertainties for each lamp into a final participant uncertainty (Section 4.2.3), and in the calculation of the pilot transfer uncertainty (Section 4.3.4). These changes had very little effect on the DOEs and their uncertainties from the values presented in Draft A v1.0.

3.9.3 Draft A v2.1

As a results of comments upon Draft A v2.0, a slightly modified version, Draft A v2.1, was prepared. This version corrected the mathematical application of the split of the uncorrelated component of each participant lamp into correlated and uncorrelated components as described in Section 4.2.3. If a fraction f of the original uncorrelated component is taken as the final uncorrelated component, then a fraction $\sqrt{(1-f^2)}$ of the original uncorrelated component must be taken as the additional correlated component in order to keep the total final uncertainty for each lamp the same before and after the split. This correction (f=0.5) had a negligible effect upon the results.

As a result of further comments concerning the preparation of participant uncertainty analyses and the separation of uncertainties into correlated and uncorrelated components at various stages of uncertainty combination, an additional paragraph was added to the Summary.

3.10. Comparison Timetable

Table Four	
Comparison Timetable	
Activity (responsibility)	**Completion Date**
Call for participants (CCPR)	Start 2010-September-06
	End 2010-October-31
Finalise participants (pilot)	2011-March-10
Finalise and appoint Task Group (chair of WG-KC)	2011-April-15
Choice of comparison artifact (TG)	2011-August-23
CCPR approval of comparison artifact (CCPR)	2011-September-17
Develop draft Protocol (TG)	2013-July-31
Approval of draft Protocol by all participants (pilot, participants)	2013-October-25
Protocol approved by CCPR WG-KC (WG-KC)	2014-January-14
Submit KCDB entry form and technical protocol to CCPR Executive Secretary for Registration of CCPR-K3.2014 with KCDB office (pilot)	2014-January-17
Receipt of calibrated traveling standards by pilot (participants)	2014-August-26
Measurement of participants' traveling standards (pilot)	Start 2014-November
	End 2015-January
Return of traveling standards to participants (pilot/participants)	2015-July-30
Repeat measurements of traveling standards (participants)	Start 2015-February
Participant data received by pilot (participants)	2015-November-30
Pre-Draft A Process 1: Verification of reported results (pilot)	2016-January-12
Pre-Draft A Process 1: Response to 'Verification' (participants)	2016-February-09
Pre-Draft A Process 2: Distribution of uncertainty budgets (pilot)	2016-February-23
Pre-Draft A Process 2: Response to Review of uncertainty budgets, with one iteration (participants)	2016-July-11

Pre-Draft A Process 3: Distribution of “Relative Data” (pilot)	2016-July-28
Pre-Draft A Process 3: Response to “Relative Data” (participants)	2017-February-09
Pre-Draft A Process 4: Identification of outliers and consistency check (pilot/participants)	2019-May-24
Distribution of Draft A v1.0(pilot)	2019-July-24
Review of Draft A v1.0 (participants)	2020-January-09
Distribution of Draft A v2.0(pilot)	2020-January-28
Review of Draft A v2.0 (participants)	2020-March-02
Distribution of Draft A v2.1(pilot)	2020-March-19
Review of Draft A v2.1 (participants)	2020-October-09
Approval of final Draft A (participants)	2020-October-09
Submit Draft B to CCPR WG-KC for approval (pilot)	2020-October-15
Review of Draft B (CCPR WG-KC)	2021-February-24
Submit Draft B-2 to CCPR WG-KC for approval (pilot)	2021-March-11
Review of Draft B-2 (CCPR WG-KC)	2021-April-02
Approval of Draft B-2 (CCPR WG-KC)	2021-April-02
Submit Draft B-2 to CCPR for approval (pilot)	2021-April-08
Approval of Draft B-2 (CCPR)	2021-November-30
Publication of final report	2022-May-20

4. Measurement Data and Analysis

The comparison data is discussed under three basic components: the data received from each participant concerning the lamps submitted, the measurement/comparison of all these lamps at the pilot laboratory, and the repeatability of each lamp as determined by the measurements at the pilot laboratory.

4.1. Uncertainty Analysis

Participants were requested to submit uncertainty values, separated into the random (uncorrelated) and the systematic (correlated) components, for each of their lamp measurements. These components were carried throughout the analysis of the data. Weighted means were determined for most quantity values. If we use the function f to be the weighted mean of the quantities x_i, and use normalised weights ω_i, we can calculate the uncertainties for the function f as:

$$f = \sum_{i=1}^{n} \omega_i \cdot x_i \qquad (1)$$

$$\frac{\partial f}{\partial x_i} = \omega_i \qquad (2)$$

$$u_{uc}^2(f) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u_{uc}^2(x_i) = \sum_{i=1}^{n} \omega_i^2 \cdot u_{uc}^2(x_i) \qquad (3)$$

$$u_c^2(f) = \left[\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right) \cdot u_c(x_i)\right]^2 = \left[\sum_{i=1}^{n} \omega_i \cdot u_c(x_i)\right]^2 \quad (4)$$

The subscripts *uc* and *c* indicate uncorrelated and correlated, respectively. These uncorrelated and correlated uncertainties can be carried into subsequent calculations as appropriate. The final total uncertainty for the function f is given by the combination:

$$u_T^2(f) = \{(\sum_{i=1}^{n} \omega_i^2 \cdot u_{uc}^2(x_i)) + ([\sum_{i=1}^{n} \omega_i \cdot u_c(x_i)]^2)\} \quad (5)$$

4.2. Participant Lamp Data

4.2.1 Participant Lamp Luminous Intensity values for each measurement round

For each round, participants were requested to make at least 2 independent (after full realignment) sets of measurements of luminous intensity on each lamp and to record/report the results, with uncertainties, in their submission of data to the pilot. Some of the participants submitted the data for each set of measurements. In these cases, the pilot was able to calculate weighted means and uncertainties, with weights determined from the uncorrelated uncertainties, as indicated in Section 4.1 above. The random/systematic components submitted by the participants were directly used as uncorrelated/correlated for these calculations. Some participants indicated that they had performed several sets of measurements, but only submitted the final values determined from these sets of measurements. In these cases, the pilot used the participants' values as the final values for the luminous intensity for each lamp.

4.2.2 Participant Lamp Luminous Intensity values: combined Round#1 and Round#2

The final comparison value of the luminous intensity of each lamp was determined as the weighted mean of the values obtained from each round (Section 4.2.1), with the uncorrelated and the correlated uncertainties for this final value determined as indicated in Section 4.1 above. The pilot assumed that the same random/systematic (uncorrelated/correlated) uncertainties submitted by the participants for each lamp were the same for each round. This does have the effect of reducing the uncorrelated uncertainty for the final luminous intensity of each lamp. Some participants indicated the final values they applied to their lamps from the results of both rounds. In these cases, the pilot used the participant values as the final values.

4.2.3 Average Uncertainty of Measurement for each participant

The uncertainty in each participant's representative luminous intensity 'scale', exemplified by the uncertainties in the luminous intensity values of each lamp, as determined in Section 4.2.2 above, can be determined using equations (3) to (5). If fractional standard uncertainties are used for the $u_{uc}(x_i)$ and the $u_c(x_i)$ in equations (3) and (4), the final fractional standard uncertainty of the participant representative luminous intensity, as embodied in the travelling standard lamps, can be determined with equation (5). This enables the combination of uncertainties from lamps with different luminous intensities, especially if the participant used both Osram and Polaron lamps.

In Draft A v1.0 the weights used were determined from the final (equation (5)) absolute uncertainties for each lamp. For Draft A v2.0 the weights used were also determined from the final (equation (5)) uncertainties for each lamp, but using fractional values. See Section 3.9.2 above. This had very little difference on the final values.

In Draft A v1.0 the uncorrelated/correlated components of each lamp uncertainty used for the uncertainty of the combination of all the lamps for each participant was assumed to be the same as for the uncorrelated/correlated combination of repeat measurements of that lamp as used in Sections 4.2.1 and 4.2.2. Concern was expressed that this may have reduced the uncorrelated components incorrectly. See Section 3.9.3 above. For Draft A v2.0 the uncorrelated component of each participant lamp, resulting from the calculations in Section 4.2.2 above, has been divided equally into two parts: one part considered uncorrelated for this NMI combination, and the other part considered correlated for this NMI combination. This also had very little difference in final comparison values.

It was pointed out that a 50:50 split of the uncorrelated component did not result in maintaining the same final combined uncertainty for the lamp luminous intensity. This was corrected in Draft A v2.1 by noting that if a fraction f of the original uncorrelated component is taken as the final uncorrelated component, then a fraction $\sqrt{(1-f^2)}$ of the original uncorrelated component must be taken as the additional correlated component in order to keep the total final uncertainty for each lamp the same before and after the split. With $f = 0.5$ this also had very little difference in final comparison values.

The participant lamp data is summarised in Appendix C.

4.3. Measurements at Pilot

4.3.1 NRC Measurement Configuration

The basic measurement procedures used at the pilot were discussed in Section 2.6.1 above, including reference to the Technical Protocol of this comparison. The schematic of the NRC measurement configuration from the Protocol is reproduced here in Figure One.

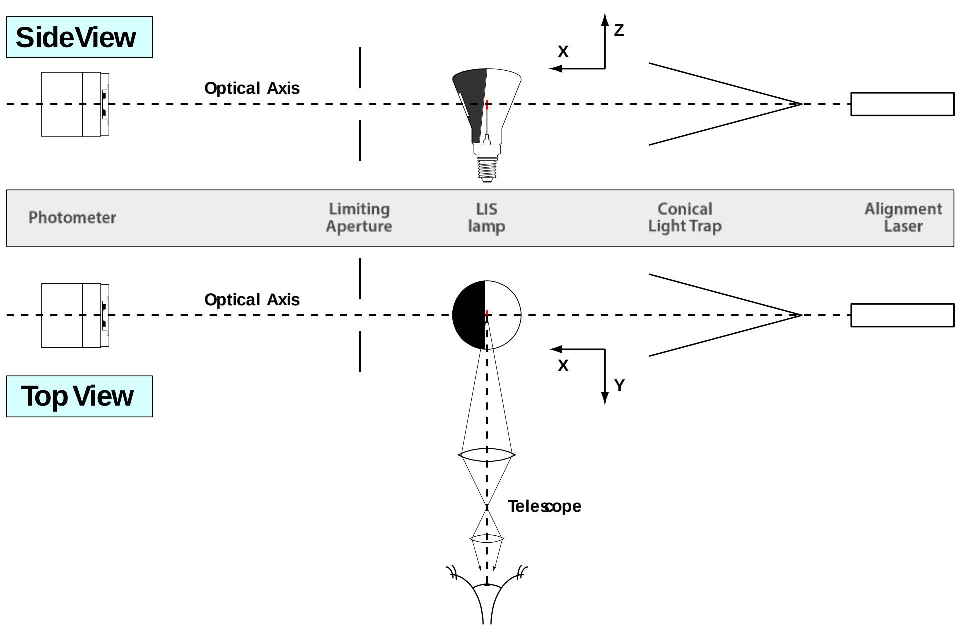


Figure One
Schematic of NRC Measurement Configuration
LIS = Luminous Intensity Standard (Osram lamp shown)

The photometer measurement position consisted of three photometers mounted on a computer-controlled linear table. The motion was along the Y-axis (horizontal). This enabled measurements by three photometers sequentially for each lamp measurement. There were three cycles of measurement for each lamp lighting. Each cycle consisted of the measurements:

> Lamp current, lamp voltage, photometer #1, photometer #2, photometer #3, lamp current lamp voltage. Since there were shutters in front of each photometer, photometer zero measurements were taken before and after the photometer signal measurements. Each of all these (13) measurements was a sequence of 5 voltmeter readings.

The use of three photometers gave one measure of the stability of the measurement configuration during the comparison. The data from one photometer was discarded due to drift that was traced to a mechanical instability in the mounting of the photometer upon the linear table. The remaining two photometers gave almost identical results. Consequently, the data from only one of these photometers was used for the final analysis.

Further discussion of the NRC measurements is given in the following uncertainty analysis for the comparison measurements.

4.3.2 Uncertainty of Comparison Measurements at Pilot (NRC)

A summary of the uncertainties is presented in Table Five. The column 'Combination Type' indicates the correlation between the variables for the purpose of combining participant lamp measurements.

1	Alignment of Z-axis	correlated	0.0000002
2	Alignment of Y-axis (Telescope optical axis)	correlated	0.0000025
3	Spectral Mismatch Error	correlated	0.0001
4	Responsivity Drift	uncorrelated	0.0005
5	Signal Noise/fluctuations	uncorrelated	0.000001
6	Alignment to optical axis (Y-Z center)	correlated	0.000000
7	Alignment to optical axis (Y-Z angular)	correlated	0.000000
8	Standard resistor calibration	correlated	0.0000042
9	DVM voltage calibration (lamp current)	correlated	0.00007
10	Lamp current setting	uncorrelated	0.0000498
11	Lamp current fluctuations	uncorrelated	0.0000616
12	Vertical filament plane (Z-axis)	uncorrelated	0.000140
13	Vertical filament plane (Y-axis)	uncorrelated	0.000035
14	Lamp to Photometer distance	uncorrelated	0.0003
15	Lamp output fluctuations (Osram/Polaron)	uncorrelated	0.0000262 / 0.0002322
	(Osram/Polaron)		0.061% / 0.065%
	(Osram/Polaron)		0.012% / 0.012%
	(Osram/Polaron)		0.062% / 0.066%

4.3.2.1 Angular Uncertainties

As indicated in the protocol, the measurand is the luminous intensity of an incandescent lamp in a specified direction from a defined point on a reference plane defined by the plane of the lamp filament. The required measurement optical axis passes through the center of the filament, and is perpendicular to the plane of the filament (Osram Wi41/G), or to the rear surface of the front window of the lamp envelope (Polaron). Setting to the normal of a plane does not fix the rotation of the plane about the normal. In our case, this is a rotation about the X-axis. In the case of the Osram lamps with the lower filament support, rotation about the X-axis was adjusted until a plumb line is visually equidistant from the two filament wires at the center of the filament. In the case of the Osram lamps with a filament with the center support, the horizontal sections on each side of the filament are aligned along the Y-axis (horizontal). The side of the lamp envelope was used to set the lamp envelope of the Polaron lamps to vertical. It is assumed that the uncertainty of lamp intensity due to an uncertainty in the rotation about the X-axis may be neglected.

The geometric measurement configuration involves two basic components: an optical coordinate system with the 3 orthogonal axes, and the components required to set the photometers and the participant lamps to this coordinate system.

The measurement optical axis is given by the horizontal laser beam to define the X-Axis as indicated in Figure One. The telescope is then set to indicate the Y and Z axes.

The lamp mount enabled the rotation of the lamp about all 3 axes and the motion of the lamp along all three axes.

The uncertainties in the luminous intensity as a result of the uncertainties in setting up the required angles for the lamp positioning follow the analysis presented in the CIE publications [8, 9]. The luminous intensity distribution of the lamps as a function of the two angles of rotation about the Y and Z axis is discussed in reference [9, section 1.10 Lamp Properties]. The example given uses modified cosine functions in the two angles, where modified means exponents to the cosine functions, and rectangular probability distributions (RPD) for the uncertainties in the alignments. The equations for the uncertainties are developed in the main document (reference [8], section 3.3.4 "Cosine Function as Non-linear Example"). The cosine function is replaced with a non-linear series (1st and 2nd terms in Taylor expansion), the shift in the average values below cos(0)=1.0 is 'ignored' and the uncertainty is increased to take up this error. The result is that the measurement uncertainty of the luminous intensity due to angular uncertainty is given by the modified/serialized/shifted cosine function as

$$u_{rel}^2(I) = \frac{g^2 \cdot \theta_{max}^4}{20} \tag{6}$$

Where

$$I(\theta) = I_0 \cdot cos^g(\theta) \approx I_0\left(1 - \frac{g \cdot \theta^2}{2} + O[3]\right), replaced\ by\ I_0$$

and θ_{max} is the limit of the rectangular probability distribution.

The uncertainties in the angles used in these measurements are small. It is assumed that the choice of g=1 gives a reasonable estimate of the associated uncertainties in the luminous intensity. Equation (6) is used to estimate the uncertainties in the pilot uncertainty budget that are due to angular uncertainties.

4.3.2.2 NRC Optical Coordinate System

The uncertainties associated with setting up the 3D orthogonal coordinate system for measuring the lamps are basically the two uncertainties in establishing the Z-axis and the Y-axis, listed as uncertainties 1 and 2 in Table Five. The Y- and Z-axes are set with respect to the X-axis laser beam using a commercial right-angle prism that has a quoted angular uncertainty of 2 arcmin. This is aligned to the laser beam using retroreflection from two plane faces of the prism.

Uncertainty #1: Alignment of Z-axis: This is composed of three components: the accuracy of the prism angles, the accuracy of the laser retroreflection, and, for the purposes of aligning the lamp filament plane for rotation about the Y-axis, the accuracy of our lamp mount in motion along the Z-axis.

Uncertainty #2: Alignment of Y-axis: This is composed of three components: the accuracy of the prism angles, the accuracy of the laser retroreflection, and the accuracy of the alignment of the telescope optical axis along the Y-axis laser beam from the prism. The latter is the predominant contributor to this uncertainty.

4.3.2.3 NRC Photometer

Uncertainty #3: Photometer Spectral Mismatch Error: The relative spectral responsivities of the three commercial photometers used were measured in our laboratory. The Spectral Mismatch Error (F*) calculated for Planck radiators between 2800 K and 2900 K indicated a change in F* from +0.01% to -0.01%. A Type B uncertainty of 0.01% was applied to all measurements and no corrections were made to individual lamps.

Uncertainty #4: Photometer Responsivity Drift: Since each comparison lamp was measured at least two times, an estimate of the potential photometer drift may be made from the changes in the measurements on the lamps. An estimate of the possible change over the course of the measurements was 0.1%. (This value could include any drift in lamp output such as due to ageing.) Since the final value for the lamp measurements is an average of all the measurements on that lamp, an estimate of the uncertainty due to possible photometer drift of 0.05% is used. See also Section 4.3.3 below, which uses the standard deviation of the mean values for individual lamps for the lamp reproducibility.

Uncertainty #5: Photometer Signal Noise/Fluctuations: The fluctuations in the photometer signal due to the photometer itself were estimated from the fluctuations in the zero signals of the photometer for the measurements.

Uncertainty #6: Photometer Alignment to optical axis (Y-Z center): This is the positioning of the center of the photometer input aperture on to the X-axis. A small displacement in the Y-Z plane at 3.2 m from the lamp causes a negligible change in the measured signal.

Uncertainty #7: Photometer Alignment to optical axis (Y-Z angular): This is the angle of the photometer input aperture with respect to the X-axis. It is determined by the reflection of the laser beam back upon itself. At perhaps 1 or 2 mm in 3.2m, it causes a negligible uncertainty.

4.3.2.4 Participant Lamps - Electrical

Uncertainty #8: Standard Resistor Calibration: The relative uncertainty in the calibration of the standard resistor used to determine the electrical current through the lamps is 0.6ppm. If we use a factor of 7 for the effect on the lamp output, we have an uncertainty of 4.2 ppm, or 0.0000042.

Uncertainty #9: DVM voltage calibration (lamp current): The DVM used to measure the voltage across the standard resistor for determining the lamp current was verified to 0.001%, or 0.00001. If we use a factor of 7 for the effect on the lamp output, we have an uncertainty of 0.00007.

Uncertainty #10: Lamp current setting: Since we measured the lamp currents for each lamp (see Section 4.3.1), we can compare the difference between the measured value and the NMI set value. The average difference was -0.00021% with scatter of 0.00068%. Instead of correcting for the shift, a larger uncertainty may be calculated by combining the two [Reference (8), equation (22)]:

$$u^2 = (0.0000021)^2 + (0.0000068)^2 => u = 0.0000071$$

This is an uncertainty in current, so the commensurate uncertainty in lamp output is scaled by a factor of 7 as we did for Uncertainties 8 and 9.

Uncertainty #11: Lamp current Fluctuations: Since we measured the lamp current 30 times at each lighting, we can calculate the fractional standard deviation for each lighting, and then calculate an average value for all the lamps and lightings. This gave a result of 0.0000088. This is an uncertainty in current, so the commensurate uncertainty in lamp output will be scaled by a factor of 7 as we did for Uncertainties 8 and 9.

4.3.2.5 Participant Lamps - Optical

Uncertainty #12: Vertical Filament Plane (Z-axis): This is the uncertainty in luminous intensity caused by the uncertainty in aligning the filament plane parallel to the Z-axis for a rotation about the Y-axis. For the case of lamps with center filament support where only one-half of the filament is visible, estimate an uncertainty of 0.2 mm in the 8 mm visible. Using the equations from Section 4.3.2.1, we obtain the estimated uncertainty of 0.000140.

Uncertainty #13: Vertical Filament Plane (Y-axis): This is the uncertainty in luminous intensity caused by the uncertainty in aligning the filament plane parallel to the Y-axis for a rotation about the Z-axis. Estimate an uncertainty of 0.2 mm in the 16 mm of the filament plane. Using the equations from Section 4.3.2.1, we obtain the estimated uncertainty of 0.000035.

Uncertainty #14: Lamp to Photometer Distance: This is the uncertainty in luminous intensity caused by the uncertainty in setting the lamp filament plane to the telescope crosshair focus point. Estimate 0.5 mm, which results in a relative standard uncertainty in luminous intensity of:

$$u = 2 * \frac{0.5}{3200} = 0.0003$$

4.3.2.6 Participant Lamps - Photometric

Uncertainty #15: Lamp Output Fluctuations: This was estimated from the average fractional standard deviation in all the photometer measurements of all the lamps. It was different for the two types of lamps (Osram and Polaron).

4.3.3 Transfer Lamp Reproducibility at Pilot

Most participant lamps were measured at the pilot only two times. The reproducibility of each transfer lamp was estimated as the standard deviation of the mean of all the (*m*) measurements of the lamp at the pilot. While this value may contain effects of photometer drift (Section 4.3.2.3 above), and is based on only a few (*m*) measurements, it gives information concerning the scatter of the (*m*) pilot measurements about their mean value.

4.3.4 Pilot Measurement Data

The Pilot measurement data for each participant lamp is summarised in Appendix D. The NMI Lamp Luminous Intensity values are taken from Appendix C (Section 4.2). The column *R(i,j)* is the average photometer responsivity $R_{i,j}$ (see Section 2.6.2) as determined from all the (*m*) measurements of the lamp *j* of the participant *i* at the pilot laboratory. The Pilot uncertainties u_{uncorr} and u_{corr} are taken from Table Five above. The Pilot uncertainty u_{uncorr} has been reduced by the factor $1/\sqrt{m}$ where m is the number of measurements of the lamp j. The column u_{uncorr}(lamp) is the transfer lamp reproducibility as described in Section 4.3.3 above. These 5 uncertainty components (NMI u_{uncorr} and u_{corr}, Pilot u_{uncorr} and u_{corr}, and u_{uncorr}(lamp)) are combined to give the uncorrelated and correlated uncertainties of $u_{R_{i,j}}$, the uncertainty of $R_{i,j}$, the combined "NMI+Pilot" quantity. At this point the uncertainties of the NMI and the Pilot are not correlated, so the NMI total uncertainty is combined in quadrature with the Pilot correlated uncertainty to give the final correlated component for the combination of the measurements for each NMI. The uncorrelated component for this combination is the combination of the Pilot uncorrelated uncertainty (Pilot u_{uncorr}) and the lamp uncorrelated uncertainty (u_{uncorr}(lamp)).

The calculations for the determination of the average value R_i for each participant are also presented in Appendix D. The average value is a weighted mean where the weights are determined from the final 'Participant + Pilot' uncertainty $u_{R_{i,j}}$ for each lamp given in the 'combined uncertainty' column u_T (relative standard uncertainty) and subsequent u_T(cd/V). The uncertainty u_{R_i} for this weighted mean R_i is determined from the uncertainties of the individual uncertainties (uncorrelated and correlated) of $u_{R_{i,j}}$ using the formulas of equations (1) to (5).

The calculation of the uncertainties of the comparison measurements made at the pilot laboratory (transfer uncertainty of the comparison, Section 2.6.2), are also presented in Appendix D. This was calculated for each participant as the difference uncertainty

$$u_{NMI\_transfer}^2 = u_{R_i}^2 - u_{NMI}^2$$

as described in Section 5 of Appendix B of the CCPR Guidelines [6].

4.4. Calculation of the KCRV and the DOE

4.4.1 Calculation of the KCRV

The calculations for determining the KCRV are summarised in Appendix E. The calculations for the KCRV do not include the results of the two NMIs, NMISA and LNE-CNAM, as discussed above in Sections 2.6.2, 3.8.2, 3.8.3 and 3.9.1

The column R(i) is the average R_i from Appendix D as described above in Sections 4.3.3 and 4.3.4.

The column u(NMI) is the uncertainty of the NMI luminous intensity 'scale' from Appendix C, as described above in Section 4.2.3.

The median NMI (10 NMIs) relative standard uncertainty is 0.002339, with the cutoff relative standard uncertainty value of 0.001722. As seen in the column uc(NMI), the NMI uncertainties with cutoff applied, this cutoff value is applied to four NMIs: NIM, PTB, NMIA, and NPL.

The column 'Pilot Transfer u(t)' is the transfer uncertainty of the comparison for each NMI as described above in Section 4.3.4 ($u_{NMI\_transfer}^2$) and calculated in Appendix D.

The uncertainty of R_i for each NMI, after cutoff, is the combination of three uncertainties: the uc(NMI), the Pilot transfer u(t), and the Mandel-Paule adjustment uncertainty s. The final uncertainty values are given in the two columns 'Uncertainty u(c,t,s)', one column giving the relative standard values and the second the values in cd/V for determining the weights. The resulting weights w_i for each NMI for calculating the weighted KCRV are given in the two columns 'KCRV weights wi'.

The Mandel-Paule relative standard adjustment uncertainty *s*=0.0003100 is applied in order to reduce the χ^2_{obs} value to the $\chi^2_{0.05}(\nu = 09) \approx 16.919$, as discussed above in Section 3.8.2. This Draft A v2.1 value is reduced from the previous draft values of *s*=0.0006163 (Draft A v1.0) and *s*=0.0003400 (Draft A v2.0). All values are quite small. The calculations for the Chi-square χ^2_{obs} consistency test are given in the column 'Chi-square'.

The resulting 'weighted mean with cutoff' KCRV is 86.2558 cd/V— the responsivity of the pilot photometer as determined by the measurement of a *virtual* KCRV Luminous Intensity lamp measured under the same conditions as the NMI lamps (Section 2.6.2). The Draft A v1.0 value of the KCRV was 86.2596 cd/V, and the Draft A v2.0 values of the KCRV was 86.2543 cd/V.

The uncertainty of this KCRV, 'u(KCRV)', is calculated from the data given in the three columns 'KCRV uncertainty calculation'.

$$u^2(KCRV) = \sum_i w_i^2 \cdot u^2(R_i)$$

where $u(R_i)$ is the combination of the u(NMI), without cutoff, and the 'Pilot Transfer u(t)' uncertainties. This is the uncorrelated uncertainty combination as shown in Equation (3). The value is 0.0588 cd/V, which gives a fractional standard deviation for the KCRV of 0.068%.

The calculations for the 'Outlier Test' (Section 3.8.1) are also given in Appendix E.

The calculations for the Chi-square χ^2_{obs} consistency test are given in the column 'Chi-square'.

$$\chi^2_{obs} = \sum_i \frac{(R_i - KCRV)^2}{u_i^2(c,t,s)}$$

4.4.2 Calculation of the Unilateral DOE

The calculations for the Unilateral Degree of Equivalence (D_i) for each NMI are also given in Appendix E.

$$D_i = \frac{R_i - KCRV}{KCRV}$$

with uncertainty values (k=1)

$$u_i^2 = u_{R_i}^2 + u_{KCRV}^2 - 2 \cdot \left(w_i \cdot u_{R_i}^2\right),$$

as given in equation (22) of the CCPR Guidelines (reference [6], Appendix B).

The results are plotted in Figure Two.

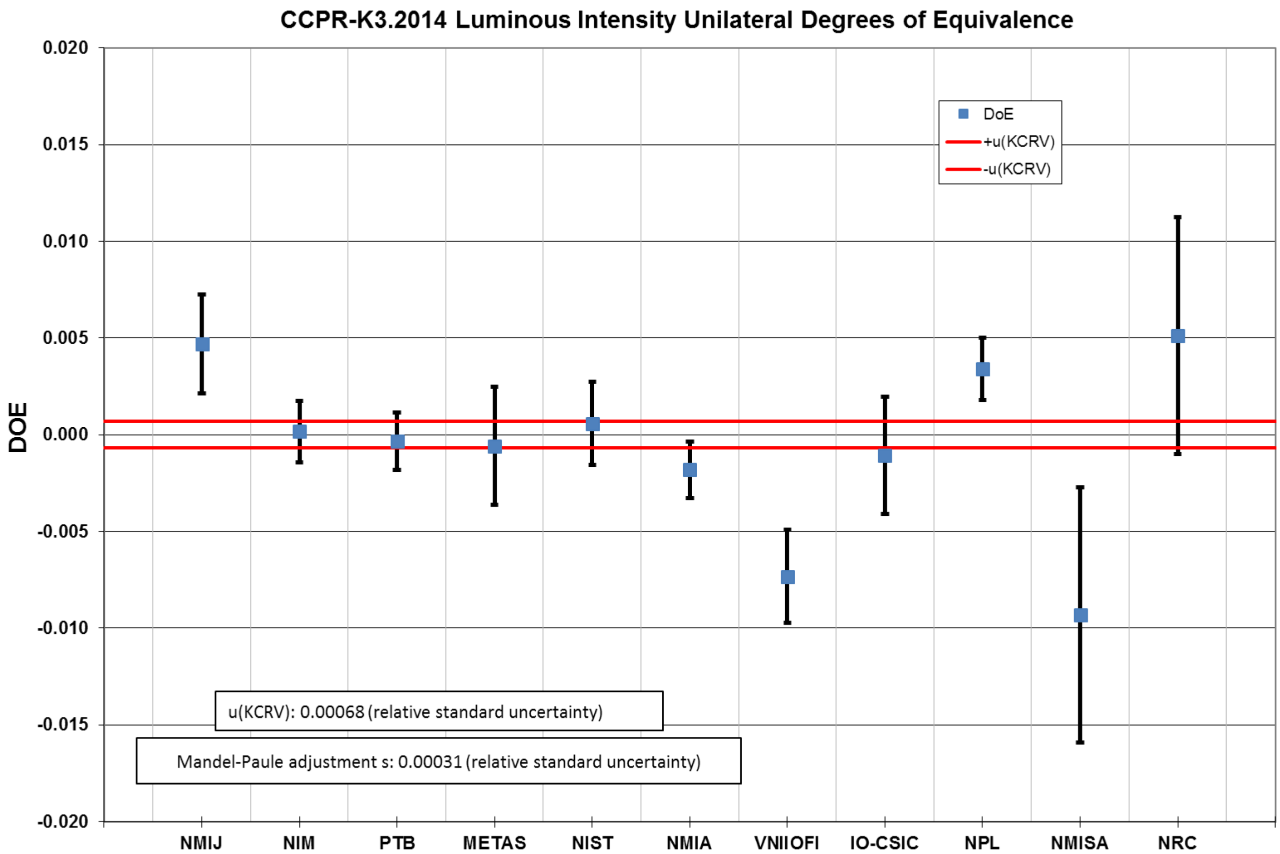


Figure Two
CCPR-K3.2014 Luminous Intensity Unilateral Degrees of Equivalence
Uncertainties are k=1 values.

4.4.3 Calculation of the Bilateral DOE

The calculations for the Bilateral Degrees of equivalence $D_{i,j}$ between NMI i and NMI j are given in Appendix F.

$$D_{i,j} = \frac{R_i - R_j}{KCRV} = D_i - D_j$$

with uncertainty values (k=1)

$$u_{i,j}^2 = u_{R_i}^2 + u_{R_j}^2$$

4.4.4 Summary Comparison Values

To assist in the subsequent linkage of the results of this comparison to subsequent bilateral and RMO comparisons, a summary of some of the calculation results of Sections 4.4.1 to 4.4.3 above is presented in Table Six. Note that for the purposes of Table Six, the uncertainties for the Unilateral DOEs are given as expanded k=2 relative uncertainties. The uncertainties associated with each participant's measurements of each of their artifacts, particularly the correlated and uncorrelated components, are described in Section 4.2 above, and detailed in Appendix C. As discussed in Sections 3.9 and 4.2 above, care should be used in the determination of when (at which stage of data analysis and combination) uncertainty components are considered correlated or uncorrelated.

KCRV relative standard (k=1) uncertainty *u(KCRV)* = 0.068%			
Mandel-Paule relative standard (k=1) adjustment uncertainty *s* = 0.031%			
			Weighting Factor w_i
NMIJ	0.0047	0.0051	0.0716
NIM	0.0002	0.0032	0.1560
PTB	-0.0004	0.0030	0.1563
METAS	-0.0006	0.0061	0.0516
NIST	0.0006	0.0043	0.0982
NMIA	-0.0018	0.0029	0.1622
VNIIOFI	-0.0073	0.0048	0.0803
IO-CSIC	-0.0011	0.0061	0.0525
NPL	0.0034	0.0032	0.1578
NMISA	-0.0093	0.0132	0.0000
NRC	0.0051	0.0123	0.0135

5. Comparison with 1999 CCPR-K3.a Key Comparison of Luminous Intensity

The results of the 1999 CCPR-K3.a key comparison, which also used incandescent lamps as transfer standards, are available at reference [1]. The unilateral DOE results for the 11 NMIs that participated in both the 1999 comparison and this comparison are presented in Table Seven and compared in Figure Three. Uncertainties are relative standard (k=1). In Figure Three, the abscissae of the two sets of data are offset slightly to enable easier comparison. The two comparisons give results that are strikingly similar.

NMIJ	-0.0009	0.0028	0.0047	0.0026
NIM	-0.0016	0.0024	0.0002	0.0016
PTB	-0.0031	0.0020	-0.0004	0.0015
METAS	-0.0050	0.0056	-0.0006	0.0031
NIST	0.0012	0.0024	0.0006	0.0021
NMIA	-0.0007	0.0030	-0.0018	0.0015
VNIIOFI	0.0033	0.0046	-0.0073	0.0024
IO-CSIC	-0.0048	0.0036	-0.0011	0.0030
NPL	0.0004	0.0015	0.0034	0.0016
NMISA	0.0051	0.0044	-0.0093	0.0066
NRC	0.0019	0.0053	0.0051	0.0061

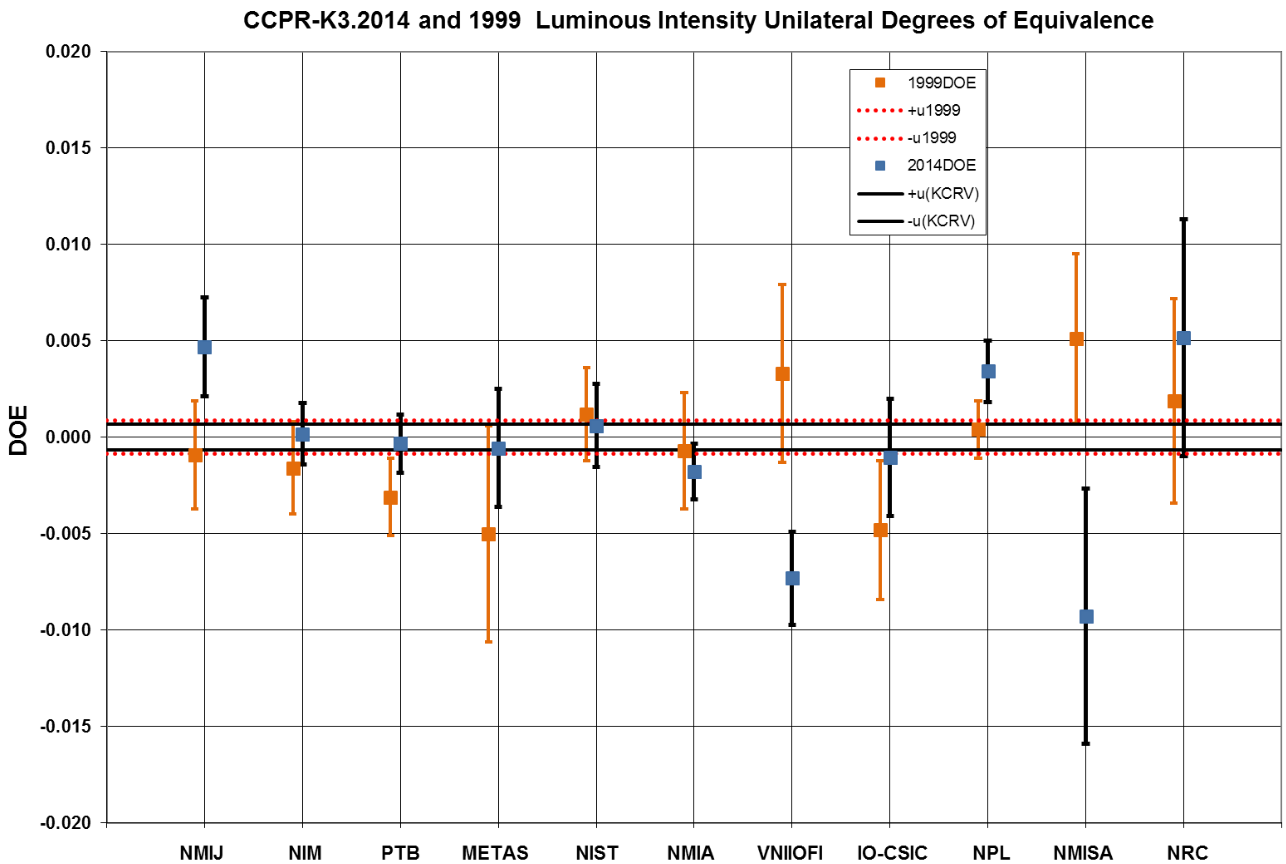


Figure Three
Comparison of CCPR-K3.a 1999 and CCPR-K3.2014
Uncertainties are relative standard (k=1)

The 1999 KCRV was determined from the results of 15 NMIs. The uncertainty of the KCRV has changed slightly from $u_{KCRV}^{1999} = 0.086\%$ to $u_{KCRV}^{2014} = 0.068\%$. As can be seen from Figure Three, this change is negligible compared to the DOE and the DOE uncertainties.

The relationships between the NMIs are also very similar for the two comparisons, with perhaps only one NMI (VNIIOFI) showing a significant shift in its DOE compared to the other NMIs. The second NMI (NMISA) with a significant shift does not have an independent LI scale and was not used for the calculation of the KCRV for this 2014 comparison.

The changes in the DOE for each NMI between the two comparisons is within the (k=1) uncertainties of the two comparisons, except for the two NMIs mentioned above (VNIIOFI and NMISA).

There has been a small change in the DOE uncertainty values u_i .The ratios $\frac{u_i^{2014}}{u_i^{1999}}$ vary from approximately 0.5 to 1.5, with an average of 0.8.

The 1999 comparison measurements were made in 1997 [1] and these 2014 comparison measurements were made in 2014. This comparison would suggest that there has not been a significant change in the luminous intensity scales of many NMIs during these 17 years. There could be several possible reasons for this observation:

1. There have been no new independent realisations of luminous intensity since 1997.

2. The primary realization of luminous intensity requires the measurement of luminous/optical power within specified geometrical conditions. Have we reached an important limitation in our measurement ability for either of these measurement challenges?

3. The primary realization of luminous intensity indicated in (2) above must be transferred to working standards and transfer standards. The CCPR comparisons used incandescent lamps as these transfer standards. Are we limited by the characteristics of these standards?

3.1 The second largest uncertainty at the pilot lab for the measurement/comparison of all the lamps was the Lamp-to-Photometer distance at 0.03%, predominantly due to the issues of aligning a non-planar thick filament plane. While this is an order of magnitude less than the typical DOE uncertainty, it is a significant component in defining the geometrical measurement conditions.

3.2 The reproducibility/repeatability/ageing/portability of the transfer standards. The average repeatability of the 62 lamps measured at the pilot was 0.09%, with a standard deviation (of the dataset) of 0.08%. While this repeatability will contain some of the realignment uncertainty (0.03%), and some of the photometer responsivity drift, it is still an important uncertainty. (Note that for this comparison it was difficult to completely separate the lamp repeatability and the photometer drift uncertainties during the pilot measurements.)

6. Summary

The CCPR Key Comparison of Luminous Intensity using incandescent lamps as transfer standards (CCPR-K3.2014) was carried out between the years of 2014 to 2020 with NRC selected as the Pilot laboratory. The 12 participants (NMIs) were selected from/by the 3 RMO groups to participate and to be willing to serve as a link laboratory to other NMIs in their RMO. The decision to use incandescent lamps rather than photometers as the transfer standards was determined by the 8-member task group after discussions with the participants. The comparison was organised as a star comparison with measurement sequence NMI-Pilot-NMI, and transfer lamps supplied by each NMI. To facilitate the measurement of all lamps from all participants under as identical conditions as possible, the measurements at the pilot did not commence until all NMI travelling standard lamps had been received at the pilot laboratory. All lamps were then measured sequentially using the same measurement set-up, over a time period of approximately 2 months during 2014-November to 2015-January.

A total of 70 transfer standards (62 of Type Osram and 8 of Type Polaron) were received at the pilot. Two lamps (Type Polaron, fixed to heavy sockets) were received at pilot broken in shipment. One lamp (Type Polaron) failed during measurement at the pilot lab. Five lamps (Type Osram) were removed from the comparison after re-measurements at the originating NMI indicated changes in the lamps larger than could be explained by the uncertainties of measurement. Three more lamps (2 Type Osram and one Type Polaron) were removed after publication of the Draft A v1.0 report. These three lamps were part of the same shipment of lamps that arrived at the pilot with two broken lamps and their withdrawal from the comparison meant the withdrawal of all the LNE-CNAM lamps from the comparison. Consequently a total of 59 lamps (55 of Type Osram and 4 of Type Polaron) were used to produce the final results of the comparison.

All participants supplied detailed reports of their measurements including uncertainty statements. These uncertainty statements have been reviewed and commented upon by all participants. Subsequent revisions and clarifications have been made, in accordance with the CCPR G2 guidelines for the preparation of comparison reports.

The KCRV is to be determined from the transfer lamps of the NMIs that have an independent realization of luminous intensity. One NMI (NMISA) did not have an independent scale, so the values of their lamps were not used in the calculation of the KCRV, although calculations of the Degree of Equivalence (DOE) were determined for all 11 (final) participants.

The KCRV was calculated as a weighted mean with 'cut-off'. The weights were determined based upon the NMI reported uncertainties adjusted by the 'cut-off', combined with the transfer uncertainty of the comparison and the uncertainty caused by the estimated lamp reproducibility observed during the measurements at the pilot lab. The cut-off value for the NMI uncertainty is 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 KCRV was then tested for statistical consistency with the measurement results using two criteria: testing for statistical 'outliers', and testing for statistical indications of under-estimated uncertainties using the Chi-Square (α=0.05) test, as defined in the CCPR-G2 guidelines. There were no outliers, but the data failed the Chi-square test. Further analysis indicated issues with the results of one participant, and it was agreed by all participants that the data of this participant would not be included in the calculation of the KCRV, but that the DOE would still be determined for all 11 (final) participants. The data for the remaining 10 participants still did not pass the Chi-square test and it was agreed by all participants that a (small) Mandel-Paule adjustment uncertainty (s) be applied to the calculations of the KCRV to enable the data to pass the Chi-Square (α=0.05) test. This uncertainty (s=0.031%) was comparable to the KCRV uncertainty u(KCRV)=0.068% and the average pilot transfer uncertainty u(t)=0.046%, but small compared to the cut-off uncertainty of 0.17% or the median NMI uncertainty of 0.23%.

The unilateral and bilateral DOE have been calculated for all 11 (final) participants. Of the 10 participants whose data were used to calculate the KCRV, 8 participants had unilateral DOEs consistent with their DOE uncertainties at the k=2 level, one participant had DOE just above the k=2 level, and one participant had DOE just above the k=3 level.

The results have not changed substantially since the last CCPR comparison 1999 CCPR-K3.a Key Comparison of Luminous Intensity with Lamps as Transfer Standards piloted by PTB.

The submission, organisation and itemisation of uncertainty components, contributions and correlations are an important part of key comparisons: for the evaluation of participant results, the combination of all participant uncertainties into a final KCRV with its uncertainty and participant DOEs, and the linkage of the key comparison results to subsequent RMO comparisons. The submission of the uncertainty budgets by each participant must be structured to enable the subsequent use of this information to all these purposes. This is becoming no longer a simple uncertainty budget table. Each uncertainty component will be combined with the other uncertainty components in different ways (correlated/uncorrelated) at the different stages of the final comparison data analysis. For example, in this comparison uncertainty components are combined in at least five stages: repeat measurements of each lamp by each participant at round #1 measurements, then repeat measurements of each lamp by each participant at round #2 measurements, then combination of the two round values into one final value for the lamp, then combination of all lamps from each participant into a final participant representative value, and finally the combination with the measurements of each lamp at the pilot to estimate a KCRV, DOEs and their uncertainties. The correlations between uncertainty components will change for each stage. In addition, the determination of the weighting methods (relative uncertainties, absolute uncertainties, or other) used for each of these combinations needs to be considered.

The method for combining measurement values and their uncertainties will also depend upon the purpose of the key comparison: to obtain a best worldwide determination of the value of the candela unit, to determine current NMI measurement capability (best or calibration level), or in some way to justify CMC claims.

The protocol developed for this key comparison did not anticipate the detail and documentation required to address this amount of detail in uncertainty evaluations, which was later noted by several participants during the pre-draft A and Draft A stages of the report preparation. However, the protocol did identify the use of the CCPR G2 guideline that was followed reasonably closely for this comparison.

Nevertheless, the several versions of the Draft A with several changes to the combination of the uncertainties showed that the differences in the final KCRV and DOE values and their uncertainties were very small between different methods of combining the measurement values and uncertainties. This may indicate that a more important aspect indicated by this key comparison is the absolute accuracy of the primary luminous intensity scales developed by each participant and/or the suitability of present travelling transfer artefacts to evaluate the relationships between the participants at the uncertainty levels presently attainable by the participants in developing their luminous intensity values.

The pilot laboratory (NRC) would like to thank all the participants for their constructive support and collaboration during the course of this comparison. The intercontinental, international, shipment of fragile transfer standards requires considerable effort from all participants. The subsequent evaluation of transfer standard data acceptability and measurement analysis requires collaboration from all participants. The pilot is grateful that all participants have readily participated during the many facets of the comparison.

7. Acronyms

BIPM	Bureau International des Poids et Mesures
CCPR	Consultative Committee for Photometry and Radiometry
CCT	Correlated Colour Temperature
CIPM	Comité international des poids et measures
KC	Key Comparison
KCDB	Key Comparison Data Base
KCRV	Key Comparison Reference Value
LIS	Luminous Intensity Standard
NMI	National Metrology Institute
RMO	Regional Metrology Organization
TG	Task Group for CCPR-K3.2014
WG-KC	CCPR Working Group on Key Comparisons

8. References

[1] **K3.a**: Georg Sauter, Detlef Lindner, Matthias Lindemann, *CCPR Key Comparisons K3a of Luminous Intensity and K4 of Luminous Flux with Lamps as Transfer Standards*, PTB Bericht, PTB-Opt-62, 1999.

K3.b: R. Köhler, M. Stock, C. Garreau, *Final Report on the International Comparison of Luminous Responsivity CCPR-K3.b*, Metrologia **41**, 2004, Tech. Suppl., 02001.

Summary results are available at the BIPM Key Comparison Database (KCDB) at www.bipm.org.

[2] *Consultative Committee for Photometry and Radiometry (CCPR), Report of the 20th meeting (17-18 September 2009) to the International Committee for Weights and Measures, Version 2: amended 13 April 2011*, BIPM, Paris, file CCPR20.pdf available from www.bipm.org.

[3] CIPM MRA-D-05, *Measurement Comparisons in the CIPM MRA*, Version 1.3 October 2012, BIPM, Paris, file CIPM_MRA-D-05.pdf available from www.bipm.org.

[4] CCPR-G4, July 01, 2013 *Guidelines for preparing CCPR Key Comparisons*, CCPR WG-KC, BIPM, Paris.

[5] *Minutes of CCPR WG-KC meeting 9 July 2010, NPL, Teddington, UK*, file WGKC-10-Minutes.pdf, available from www.bipm.org.

[6] CCPR-G2 Rev.3, July 01, 2013 *Guidelines for CCPR Comparison Report Preparation*, CCPR WG-KC, BIPM, Paris.

[7] JCGM 100:2008, Joint Committee for Guides in Metrology (September 2008), Evaluation of Measurement Data — *Guide to the expression of uncertainty in measurement (GUM).* Available from http://www.bipm.org . See also JCGM 104:2009, *Evaluation of measurement Data — An introduction to the "Guide to the expression of uncertainty in measurement" and related documents.*

[8] CIE Publication 198:2011, *Determination of Measurement Uncertainties in Photometry*, Commission Internationale de l'Eclairage, Vienna, Austria.

[9] CIE Publication 198-SP1.1:2011, *Supplement 1: Modules and Examples for the Determination of Measurement Uncertainties, Part 1: Modules for the Construction of Measurement Equations*, Commission Internationale de l'Eclairage, Vienna, Austria.

9. Appendices

Appendix A NMI Reports
- Description of Measurement facility
- Record of Lamp Operating Time
- Measurement Uncertainty Budget
- Measurement Results, round#1 and #2

Appendix B Review of Uncertainty Budgets
- replies to general comments
- replies to questions to specific NMIs
- attachments
  - VNIIOFI, NPL, NMIJ, NMISA

Appendix C Summary of Participant Lamp Luminous Intensity Values

Appendix D Summary of Pilot Measurements of Participant Lamps

Appendix E Calculation of the KCRV and the Unilateral DOE

Appendix F Calculation of the Bilateral DOE

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>NMI Reports</u>

- Description of Measurement Facility

- Record of Lamp Operating Time

- Measurement Uncertainty Budget

- Measurement Results, Round#1 and #2

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>NMISA Report</u>

CCPR Key Comparison
Luminous Intensity (CCPR-K3.a)

Report by:
NMISA Photometry & Radiometry

2015-11-24

The luminous intensity of the four standard lamps was measured at the National Metrology Institute of South Africa for the CCPR-K3.2013 luminous intensity intercomparison. Measurements were performed at electrical operating conditions such that the correlated colour temperature of the luminous intensity was approximately 2 856 K.

Appendix A.3 Description of the measurement facility

A partial-filtering type LMT photometer with 60 mm Ø input aperture was used. The reference standards are Si-trap detectors (3-trap design) which have traceability to the National Physical Laboratory (NPL) where they were calibrated.

Description of Measurement Procedures

Alignment was done with a laser alignment system (which consists of two HeNe lasers) and according to the alignment procedure normally used by the NMISA for calibration of luminous intensity lamps. The alignment was done while the lamps were powered down, *i.e.* the lamp filaments were at room temperature. The centre filament support #2 was used for alignment with the defined point at the centre of the filament as shown in *Figure Two* of *Section 4.4.8* of the technical protocol.

The mounting/alignment stage used in the setup of the standard lamps is shown in Figure 1. It allows five degrees of freedom *viz.* translation on the *x*-axis and *y*-axis (5), tip and tilt (3 & 4) and rotation (1 & 2).

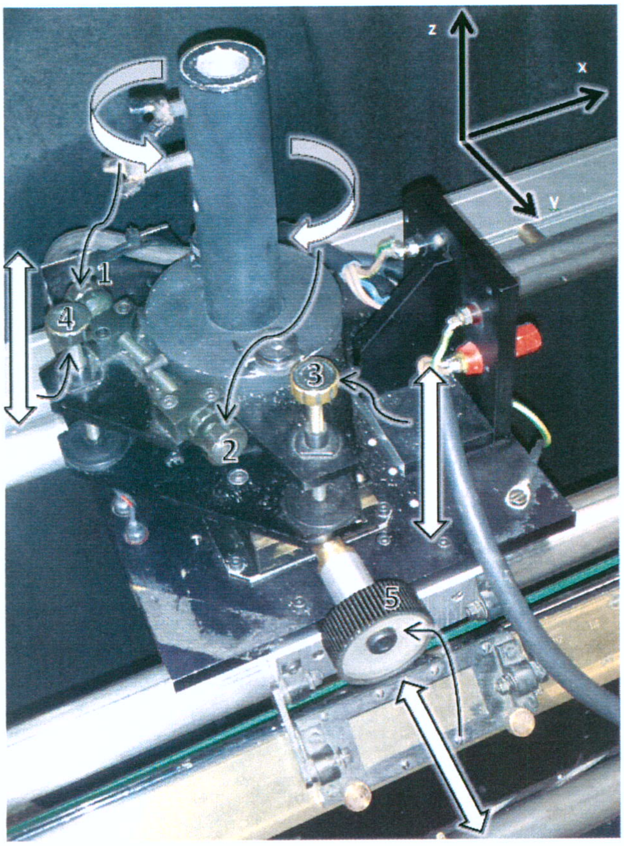


Figure 1: Explanation of the mounting/alignment stage.

1

Correlated Colour Temperature

The correlated colour temperature of each lamp was measured with a filter-photometer during the first round of measurements, and with a diode-array spectroradiometer during the second round of measurements. The measurement setup consisted of the lamp in use, a Spectralon SRS-99-020 diffuse reflectance standard with known reflectance values at 0° /45° geometry, the filter-photometer or diode-array spectroradiometer and optical baffles, all mounted on an optical bench.

Each lamp was mounted base down and aligned perpendicularly to the diffuse reflectance standard at a distance of approximately 1,0 m as measured from the centre of the lamp filament. The filter-photometer or diode-array spectroradiometer head was aligned at an angle of ~45° to the diffuse reflectance standard. The optical axis was horizontal and passed through the centre of the lamp filament and perpendicular to the plane of the lamp filament. The diffuse reflectance standard and filter-photometer or diode-array spectroradiometer head were aligned with the optical axis.

In order to reduce stray light, three 30 cm × 30 cm baffles with ~10 cm Ø apertures were placed between the lamp and the diffuse reflectance standard. A baffle tube with an ~45° extension tube and two 32 cm × 32 cm baffles with ~8 cm Ø apertures was placed between the filter-photometer or diode-array spectroradiometer, the reflectance standard and the lamp. Refer to the experimental layout in Figure 2 for the approximate distance placement of the baffles. For additional shielding, the photometric bench was surrounded by black curtains from ceiling to floor.

The reported correlated colour temperature 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 correlated colour temperatures.

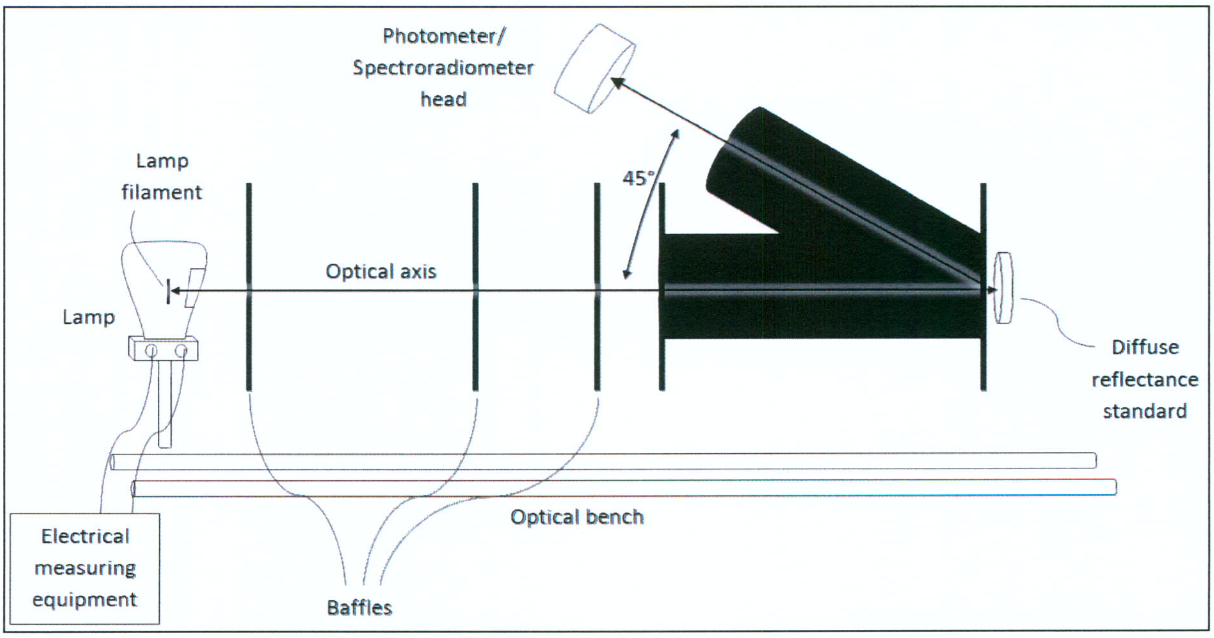


Figure 2: Diagram of experimental setup for correlated colour temperature.

<u>Luminous Intensity</u>

The lamps were connected to the power supply according to the polarity as indicated on the lamp terminals. Each lamp was mounted base down and aligned perpendicularly to the partial-filtering photometer at a distance of 2,7 m as measured from the centre of the lamp filament. The optical axis was horizontal and passed through the centre of the lamp filament and perpendicular to the plane of the lamp filament. The partial-filtering photometer was aligned with the optical axis.

In order to reduce stray light, three 30 cm × 30 cm baffles with ~10 cm Ø apertures were placed between the lamp and the partial-filtering photometer. A baffle tube with a closed ~45° extension tube and two 32 cm × 32 cm baffles with ~8 cm Ø apertures was placed between the lamp and partial-filtering photometer. Refer to the experimental layout in Figure 3 for the approximate distance placement of the baffles. For additional shielding, the photometric bench was surrounded by black curtains from ceiling to floor.

Five measurements per lamp were performed during each measurement set. The lamps were powered down, repositioned and realigned, and powered up between the different sets. The reported luminous intensity value is the average of the two sets.

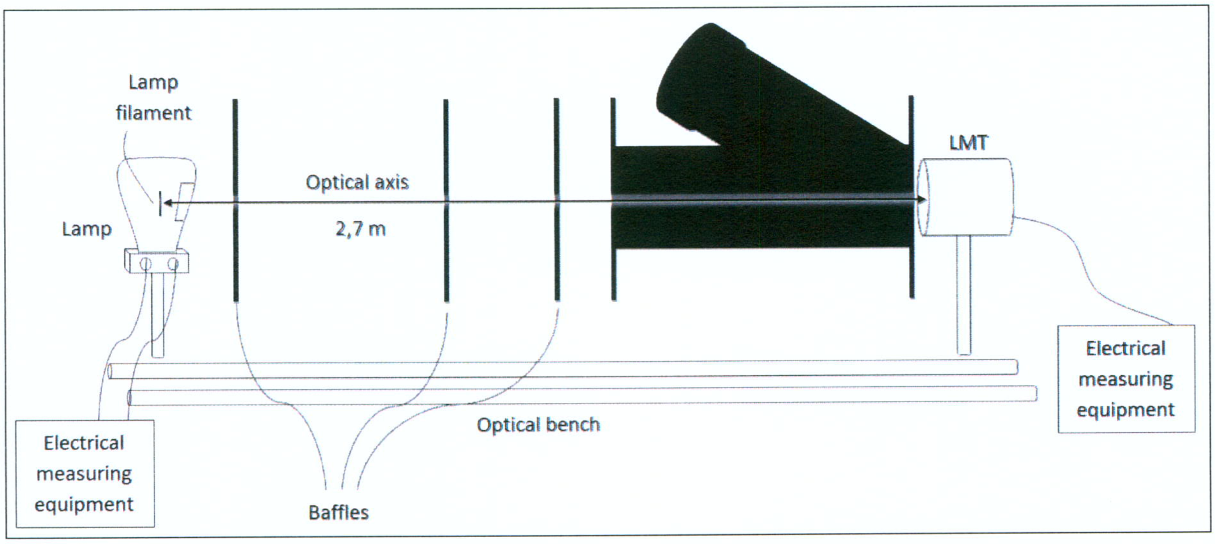


Figure 3: Diagram of experimental setup for luminous intensity.

Laboratory Conditions

The ambient conditions in the laboratory during the first round of measurements were:

- Correlated colour temperature:
    - Average Temperature = 21°C
    - Average Humidity = 39 %RH
- Luminous intensity:
    - Average Temperature = 21°C
    - Average Humidity = 40 %RH

The ambient conditions in the laboratory during the second round of measurements were:

- Correlated colour temperature:
  - Average Temperature = 21°C
  - Average Humidity = 57 %RH
- Luminous intensity:
  - Average Temperature = 20 °C
  - Average Humidity = 62 %RH

Operating conditions of the lamps

The power supply to the lamps was gradually ramped up and down. The operating currents of the lamps were set to the current values as determined during the correlated colour temperature measurements. During the Round 2 measurements the current setting of lamp NSI 10 was readjusted to achieve the required colour temperature. Results for Round 2 are reported for the Round 1 current setting and the readjusted current setting.

The lamps were allowed to stabilize for at least 10 minutes before measurements were performed. The current and voltage during the measurement period were recorded at regular intervals.

Participants: RH Sieberhagen; EM Coetzee; I Kruger; RD Pepenene; PJW du Toit; EK Mofokeng

NMI: NMISA

Date: 24/11/2015

Signatures:

Appendix A.4 Record of lamp operating time

Lamp number: "24" 4595 PTB 09

Date	Activity	Burn time [hrs]	Lamp Current [amperes]	Lamp Voltage [volts]	Operator initials
Round 1					
06/05/2014	CCT measurement	0,35	5,824	30,247	EC; RS; IK; RP
19/05/2014	Measurement – 1	0,33	5,824	30,241	
20/05/2014	Measurement – 2	0,33	5,824	30,243	
Round 2					
04/08/2015	CCT measurement	0,42	5,824	30,242	EC; RS; IK; PdT; EM
05/08/2015	Measurement – 1	0,58	5,824	30,255	
05/08/2015	Measurement – 2	0,53	5,824	30,254	

Lamp number: "39" 4596 PTB 09

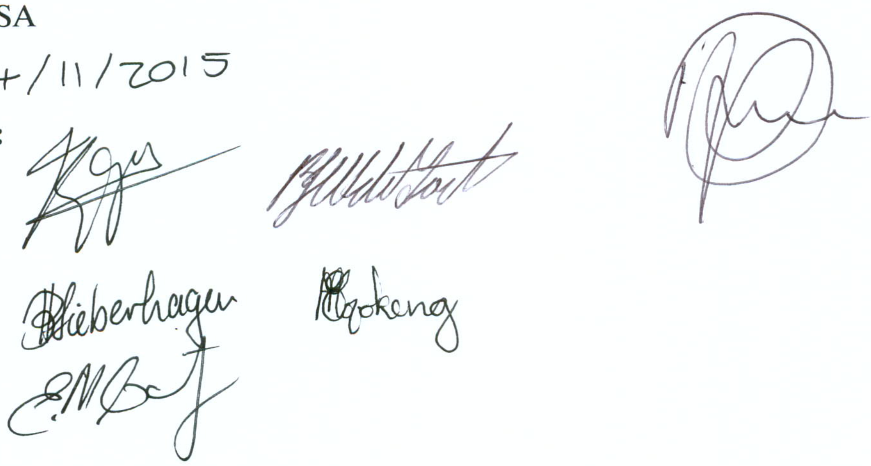
Date	Activity	Burn time [hrs]	Lamp Current [amperes]	Lamp Voltage [volts]	Operator initials
Round 1					
06/05/2014	CCT measurement	0,37	5,892	30,823	EC; RS; IK; RP
19/05/2014	Measurement – 1	0,33	5,892	30,817	
20/05/2014	Measurement – 2	0,35	5,892	30,816	
Round 2					
04/08/2015	CCT measurement	0,73	5,892	30,823	EC; RS; IK; PdT; EM
05/08/2015	Measurement – 1	0,42	5,892	30,826	
05/08/2015	Measurement – 2	0,38	5,892	30,827	

Participants: RH Sieberhagen; EM Coetzee; I Kruger; RD Pepenene; PJW du Toit; EK Mofokeng

NMI: NMISA

Date: 24/11/2015

Signatures:



Lamp number: "42" 4597 PTB 09

Date	Activity	Burn time [hrs]	Lamp Current [amperes]	Lamp Voltage [volts]	Operator initials
Round 1					
06/05/2014	CCT measurement	0,42	5,880	30,719	EC; RS; IK; RP
19/05/2014	Measurement – 1	0,50	5,880	30,716	
20/05/2014	Measurement – 2	0,33	5,880	30,710	
Round 2					
04/08/2015	CCT measurement	0,50	5,880	30,718	EC; RS; IK; PdT; EM
05/08/2015	Measurement – 1	0,45	5,880	30,722	
05/08/2015	Measurement – 2	0,37	5,880	30,720	
06/08/2015	Measurement – 3	0,47	5,880	30,728	

Lamp number: NSI 10

Date	Activity	Burn time [hrs]	Lamp Current [amperes]	Lamp Voltage [volts]	Operator initials
Round 1					
09/05/2014	CCT measurement	0,42	5,890	31,959	EC; RS; IK; RP
19/05/2014	Measurement – 1	0,33	5,890	31,966	
20/05/2014	Measurement – 2	0,33	5,890	31,959	
Round 2					
04/08/2015	CCT measurement – 1	0,58	5,890	31,942	EC; RS; IK; PdT; EM
06/08/2015	CCT measurement – 2	0,60	5,840	31,453	
05/08/2015	Measurement – 1	0,45	5,890	31,943	
05/08/2015	Measurement – 2	0,42	5,890	31,946	
06/08/2015	Measurement – 3	0,58	5,724	30,292	
06/08/2015	Measurement – 4	0,48	5,724	30,289	
06/08/2015	Measurement – 5	0,50	5,840	31,456	
06/08/2015	Measurement – 6	0,38	5,840	31,459	

Participants: RH Sieberhagen; EM Coetzee; I Kruger; RD Pepenene; PJW du Toit; EK Mofokeng

NMI: NMISA

Date: 24/11/2015

Signatures:

6

Appendix A.5 Measurement Uncertainty Budget

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of working standards		
- reference photometer	B	0.6500
Electrical		
- standard resistor	B	0.0037
- voltmeter	B	0.0009
Photometer		
- distance	B	0.0091
- spatial uniformity	B	0.0577
Environment		
- stray light	A	0.0300
RMS total systematic effects:		0.6533
Random effects:		
Lamp parameters:		
- lamp ageing	A	0.0631
- lamp alignment	A	0.1424
- lamp output fluctuations (lamp voltage)	A	0.0031
Electrical parameters:		
- power supply fluctuations	A	0.0005
Photometer noise:	A	0.0001
(Measurement Set standard deviation of mean):	A	0.0033
RMS total random effects:		0.1558
RMS total standard uncertainty (k = 1):		0.68

Participants: RH Sieberhagen; EM Coetzee; I Kruger; PJW du Toit; EK Mofokeng

NMI: NMISA

Date: 10/12/2015

Signatures:

Appendix A.6 Measurement Results

Measurement Round #1:

Lamp number: "24" 4595 PTB 09

Measurement Set Number	Number of measurements per set	Date	Lamp current [A]	Lamp voltage [V]	Correlated colour temperature [K]	Luminous Intensity [cd]
#1	5	19/05/2014	5,824	30,241		
#2	5	20/05/2014	5,824	30,243		
Average			**5,824**	**30,242**	**2 841**	**269,0**

Lamp number: "39" 4596 PTB 09

Measurement Set Number	Number of measurements per set	Date	Lamp current [A]	Lamp voltage [V]	Correlated colour temperature [K]	Luminous Intensity [cd]
#1	5	19/05/2014	5,892	30,817		
#2	5	20/05/2014	5,892	30,816		
Average			**5,892**	**30,816**	**2 853**	**283,9**

Lamp number: "42" 4597 PTB 09

Measurement Set Number	Number of measurements per set	Date	Lamp current [A]	Lamp voltage [V]	Correlated colour temperature [K]	Luminous Intensity [cd]
#1	5	19/05/2014	5,880	30,716		
#2	5	20/05/2014	5,880	30,710		
Average			**5,880**	**30,713**	**2 848**	**274,6**

Lamp number: NSI 10

Measurement Set Number	Number of measurements per set	Date	Lamp current [A]	Lamp voltage [V]	Correlated colour temperature [K]	Luminous Intensity [cd]
#1	5	19/05/2014	5,890	31,966		
#2	5	20/05/2014	5,890	31,959		
Average			**5,890**	**31,962**	**2 854**	**314,4**

Participants: RH Sieberhagen; EM Coetzee; I Kruger; RD Pepenene

NMI: NMISA

Date 24/11/2015

Signatures: RH Sieberhagen

8

Measurement Round #2:

Lamp number: "24" 4595 PTB 09

Measurement Set Number	Number of measurements per set	Date	Lamp current [A]	Lamp voltage [V]	Correlated colour temperature [K]	Luminous Intensity [cd]
#1	5	05/08/2015	5,824	30,255		
#2	5	05/08/2015	5,824	30,254		
Average			**5,824**	**30,254**	**2 838**	**268,7**

Lamp number: "39" 4596 PTB 09

Measurement Set Number	Number of measurements per set	Date	Lamp current [A]	Lamp voltage [V]	Correlated colour temperature [K]	Luminous Intensity [cd]
#1	5	05/08/2015	5,892	30,826		
#2	5	06/08/2015	5,892	30,827		
Average			**5,892**	**30,826**	**2 849**	**284,4**

Lamp number: "42" 4597 PTB 09

Measurement Set Number	Number of measurements per set	Date	Lamp current [A]	Lamp voltage [V]	Correlated colour temperature [K]	Luminous Intensity [cd]
#1	5	05/08/2015	5,880	30,722		
#2	5	06/08/2015	5,880	30,728		
Average			**5,880**	**30,725**	**2 844**	**277,1**

Lamp number: NSI 10

Measurement Set Number	Number of measurements per set	Date	Lamp current [A]	Lamp voltage [V]	Correlated colour temperature [K]	Luminous Intensity [cd]
#1	5	05/08/2015	5,890	31,943		
#2	5	05/08/2015	5,890	31,946		
Average			**5,890**	**31,944**	**2 869**	**317,2**
#1	5	06/08/2015	5,840	31,456		
#2	5	06/08/2015	5,840	31,459		
Average			**5,840**	**31,458**	**2 855**	**299,3**

Participants: RH Sieberhagen; EM Coetzee; I Kruger; RD Pepenene; PJW du Toit; EK Mofokeng

NMI: NMISA

Date: 24/11/2015

Signatures:

NMISA:

Model of evaluation:

See attached page for NMISA Uncertainty Budget Matrix (UBM).

$$I = \frac{K_m d^2 F I_c}{SA}$$

where

I is the luminous intensity

K_m is the luminous efficacy

d is the distance from the lamp filament to the photometer

F is the spectral mismatch factor

I_c is the current, determined for the gain of the amplifier and the voltage as measured for the LMT photometer

S is the responsivity of the LMT photometer

A is the area of the LMT photometer

- Spectral mismatch: We corrected for spectral mismatch and therefore did not include it in the model of evaluation.
- Lamp alignment: We allowed for 1° uncertainty in the alignment of the lamps, as you can see in the model of evaluation.

UNCERTAINTY BUDGET MATRIX (UBM)	Certificate No	
	Procedure No	

Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9)

Description:	CCPR-K3 Luminous Intensity Intercomparison	**Type & Serial Number**		**Range:**		**Metrologist**

Mathematical Model:

Symbol	Input Quantity (Source of Uncertainty) *(X i)*	Estimated Input Quantity *(x i)*	Estimated Uncertainty	Unit	Probability Distribution (N, R, T, U)	k= ▼	Divisor factor	Standard Uncertainty *U(Xi)*	Sensitivity Coefficient *Ci*	Unit	Standard Uncertainty Contribution *Ui (y)*	Reliability %	Degrees of Freedom *v*	Remarks
	▼ Standards and Reference Equipment (Uncorrelated) ▼										**Unit**			
Std	Photometer (LMT)		1.300000	%	Normal k = 2		2.00	6.500E-01	1.000E+00		6.500E-01	100.00	infinite	From certificate OR\SR-5082
	Spatial uniformity		0.100000	%	Rectangular √3		1.73	5.774E-02	1.000E+00		5.774E-02	95.00	200.00	Literature Type B
	Distance uncertainty		0.018170	%	Normal k = 2		2.00	9.085E-03	1.000E+00		9.085E-03	100.00	infinite	Optical bench certificate DM\DIM-4016 type B
	Lamp fluctuations during operation (lamp stability		0.003100	%	Normal k = 1		1.00	3.100E-03	1.000E+00		3.100E-03	100.00	infinite	Empirical test Type A, I:\Laboratories\Optical Radiomet
	Lamp alignment		1.000000	deg	Rectangular √3		1.73	5.774E-01	2.467E-01	%/deg	1.424E-01	100.00	infinite	Empirical test PH-03, sens coef unit is %/deg type A
	Electrical noise on photometer signal		0.000100	%	Normal k = 1		1.00	1.000E-04	1.000E+00		1.000E-04	100.00	infinite	Empirical test Type A, I:\Laboratories\Optical Radiomet
	Lamp power setting (lamp current)		0.000450	%	Normal k = 1		1.00	4.500E-04	1.000E+00		4.500E-04	100.00	infinite	Empirical test Type A, I:\Laboratories\Optical Radiometr
	Drift/ageing of lamps		0.063100	%	Normal k = 1		1.00	6.310E-02	1.000E+00		6.310E-02	100.00	infinite	Type A I:\Laboratories\Optical Radiometry\Irma\Intercor
	electrical - std resistor		0.007410	%	Normal k = 2		2.00	3.705E-03	1.000E+00		3.705E-03	100.00	infinite	Certificates, type B, I:\Laboratories\Optical Radiometry\
	electrical - voltmeters		0.001760	%	Normal k = 2		2.00	8.800E-04	1.000E+00		8.800E-04	100.00	infinite	Certificates, type B, I:\Laboratories\Optical Radiometry\
	Stray light		0.030000	%	Normal k = 1		1.00	3.000E-02	1.000E+00		3.000E-02	100.00	infinite	Empirical test Type A, I:\Laboratories\Optical Radiomet
Res	Resolution of Standard / Equipment (If applicable)											100		
	▼ Standards and Reference Equipment (Correlated) ▼							**NOTE!**	*ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED*					
	▼ Unit Under Test / Calibration (Uncorrelated) ▼							**NOTE!**	*ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED*					
Res	Resolution of UUT (If applicable)											100		
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		0.003	%	Normal K = 1		1.00	3.300E-03	1.000E+00		3.300E-03		4	No of Readings 5
	▼ Unit Under Test / Calibration (Correlated) ▼							**NOTE!**	*ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED*					

About UBM	**TOTAL COMBINED UNCERTAINTY**			**Unit**			
Best Measurement Capability (<u>Excluding</u> UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼		6.716E-01	V_{eff}	3662867	Checked and Approved By:
	Expanded Uncertainty	**68,27 %**	**K = 1**	**6.72E-01**	**k =**	**1.00**	
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼		6.716E-01	V_{eff}	infinite	
	Expanded Uncertainty	**68,27 %**	**K = 1**	**6.72E-01**	**k =**	**1.00**	

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>NIM Report</u>

Appendix A.3 Description of the measurement facility

Description of NIM measurement geometry

The optical configuration for luminous intensity measurement at NIM is shown schematically in Figure One. Position unit in Figure One is mm.

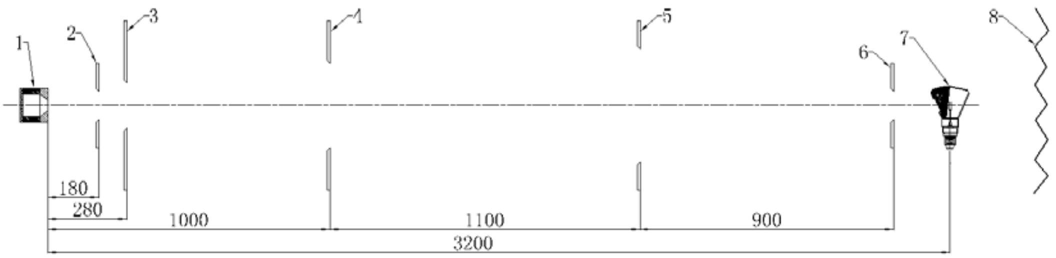


Figure One

Schematic of NIM measurement configuration:
1 photometer; 2-6 baffles; 7 luminous intensity lamp; 8 radiation trap.

The basic geometric conditions are as follows:
- The lamp is mounted base down.
- The optical axis is horizontal and passes through the center of the filament.
- The optical axis is perpendicular to the plane of the filament (Osram Wi41/G).
- Distance from the lamp is measured from the center of the filament.
- The photometric measurements accept only the light passing through the rectangular opening in the black mask on the face of the Osram Wi41/G lamp.

The distance between the photometer input aperture and the lamp filament plane on the NIM photometric bench is 3.2 m. The NIM photometer has an input aperture diameter of approximately 9 mm. Thus the solid angle for the light emitted from the lamp that is measured by the photometer is approximately 6 µsr.

In Figure One, 2-5 are baffles with rectangular aperture sizes of 50mm×50mm, 80mm×80mm, 150mm×150mm, and 200mm×200mm, respectively; 6 is a baffle located 200mm before the lamp with a 50mm diameter circular aperture; a radiation trap (8) made of a piece of black velvet cloth is mounted 2.0 m behind the luminous intensity lamp (7) to ensure the reflectance to be less than 0.02%.

Description of NIM measurement procedures

All lamps were operated with DC power at the fixed polarity and fixed current. The electrical operating parameters of the lamps were measured using the standard four-terminal measurement to permit an accurate measurement of the lamp operating current and voltage. The voltage was measured at the lamp socket, rather than the lamp base.

The lamp current was ramped up slowly over approximately one minute to the specified value. The luminous intensity of the standard lamps was measured together with the electrical values. After measurements, the lamp voltage was ramped down slowly over approximately one minute.

After connecting the electrical power to the lamp, ten minutes warm-up procedure for each lamp was followed.

The measurement is conducted on an 8 m photometric bench using a group of eight BDQ8 luminous intensity lamps as reference to calibrate a group of six Wi41/G lamps.

Lamp Wi41/G-152, Wi41/G-180, and Wi41/G-159 were calibrated on 26-01-2014 and 27-01-2014. All the six Wi41/G lamps were calibrated on 06-03-2014 and 11-03-2014. All the lamps and measurement facilities were reinstalled in each measurement.

Make and type of NIM photometer

The measurement is conducted using an LMT full filter photometer, with the following features:

- no temperature control is applied.
- the f_1’ is 1.2%.
- no diffuser is used.
- the diameter of the detector is about 9 mm.

A Keithley 6485 picometer is used for the measurement of the photocurrent.

NIM operating conditions of the lamps

NIM electrical conditions:

- DC electrical power.
- Defined fixed electrical current for each lamp operation.
- Defined electrical polarity at lamp contacts, the center is positive (+) and the side base is negative (–).
- The defined electrical current has been determined by NIM to result in a CCT between 2829 K and 2841K for the photometric output of the lamp. The actual CCT value has been report in Appendix A.6 Measurement Results.
- The warm-up time for each lamp is ten minutes.

NIM optical coordinate system:

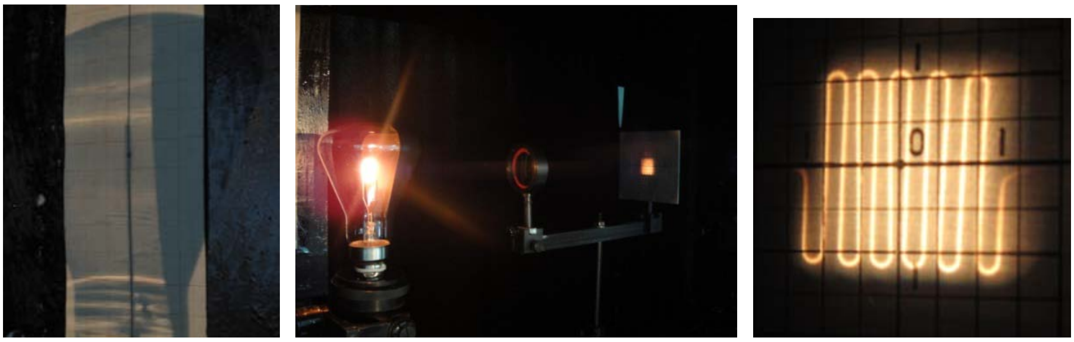
The optical axis for the measurements is the straight line between the center of the photometer input aperture and the defined point on the reference plane defined by the plane of the lamp filament. A regulator (Figure Two b) was used to align the photometer input aperture and the lamp filament center position. The axis of the regulator coincides with the photometric bench axis. The coordinate axis system is same as that illustrated in Figure One of the Luminous Intensity Technical Protocol.

The origin of the coordinate system is established in NIM using an alignment telescope. The alignment telescope is positioned such that its optical axis is identical to the optical axis of the center of the regulator and perpendicular to the indicator board. The telescope mount and the center regulator mount are adjusted such that the crosshair of the indicator board coincides with the crosshair of the telescope at any position along the X direction.

The spatial position of the lamp is defined as “For Center Filament Support #2” of the protocol. The alignment of the filament was at the room temperature.

A special carriage having five degrees of freedom in its physical adjustments was used for lamp position adjustment.

The vertical direction of the lamp was adjusted using the shadow of the filament (Figure Two a). A collimated light beam projects the lamp filament on an indicator board with a mark of line (plumb line) which is perpendicular to the optical axis. The lamp was rotated about the Z-axis until the width (in the X direction) of the shadow of the filament is minimized.



(a) (b) (c)

Figure Two
Filament alignment.

Rotation about the Y-axis is adjusted until the shadow of the filament on the indicator board is parallel to the plumb line.

A regulator (Figure Two b) is used for the filament plane and the photometer input aperture center alignment. The regulator is an optical imaging system consists of a lens and an indicator board and its optical axis coincides with the optical axis of the photometric bench. The lamp was adjusted until the filament center coincides with the crosshairs in the indicator board (Figure Two c), so that the optical axis of the photometric bench passes through the center of lamp filament plane.

Description of NIM calibration laboratory conditions

During the measurement for this comparison the ambient temperature at NIM is stabilized at 24.5℃ with fluctuations less than 1℃. The humidity is (35% -39%) RH.

Laboratory transfer standards used at NIM

BDQ8 (see Figure Three for an example) luminous intensity lamps are used as laboratory transfer standards with the following features:

- current is about 6.6000 A.
- voltage is about 97 V.
- luminous intensity is about 1230 cd.
- CCT is about 2835 K.

These lamps are made in China.

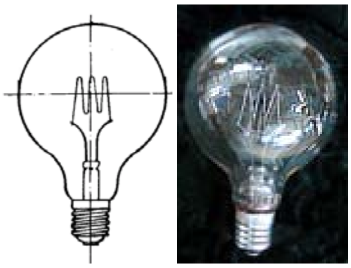


Figure Three
A BDQ8 luminous intensity lamp

Establishment or traceability route of primary scale including date of last realisation and uncertainty budget.

The luminous intensity unit was realized by a group of seven electrically calibrated radiometers of with conical cavity, precision aperture, $V(\lambda)$ filter. BDQ 8 lamps with gas-filled tungsten filament, specially developed as the secondary standard, maintaining the luminous intensity unit. The latest realization was done in 2013. The standard uncertainty for the realization is 0.16%.

Uncertainty budget for realization of the unit of luminous intensity

Uncertainty component	Type	Relative standard uncertainty/ %
Measurement of the irradiance	B	0.11
$V(\lambda)$ filter spectral transmittance at 555nm	B	0.06
Spectral mismatch	B	0.03
Distance measurement	B	0.06
Homogeneity of the lamp group	A	0.06
Current control of the lamp	B	0.05
Combined standard uncertainty		0.16

Participant: National Institute of Metrology
NMI: NIM
Date: April 12，2014
Signature: 

Appendix A.4 Record of lamp operating time

Lamp number: Wi41/G -96(NIM-01)

Date	Lamp ON time	Activity/Comments (test, alignment, measurement)	Lamp OFF time	Burn time (mins)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
06/03/2014		testing		12	5.7940	29.851	Jiang
11/03/2014		testing		12		29.841	Liu
17/08/2015		testing		12		29.829	Liu
18/08/2015		testing		24		29.826	Lv

Lamp number: Wi41/G -152(NIM-02)

Date	Lamp ON time	Activity/Comments (test, alignment, measurement)	Lamp OFF time	Burn time (mins)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
26/01/2014		testing		12	5.8184	30.013	Liu
27/01/2014		testing		12		30.013	Jiang
06/03/2014		testing		12		30.013	Jiang
11/03/2014		testing		12		30.014	Liu
17/08/2015		testing		12		30.019	Liu
18/08/2015		testing		26		30.020	Lv

Lamp number: Wi41/G -164(NIM-03)

Date	Lamp ON time	Activity/Comments (test, alignment, measurement)	Lamp OFF time	Burn time (mins)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
06/03/2014		testing		12	5.8072	29.781	Liu
11/03/2014		testing		12		29.780	Jiang
17/08/2015		testing		36		29.770	Liu
18/08/2015		testing		36		29.775	Lv

Lamp number: Wi41/G -180(NIM-04)

Date	Lamp ON time	Activity/Comments (test, alignment, measurement)	Lamp OFF time	Burn time (mins)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
26/01/2014		testing		12	5.8044	29.955	Liu
27/01/2014		testing		12		29.955	Jiang
06/03/2014		testing		12		29.955	Jiang
11/03/2014		testing		12		29.949	Liu
17/08/2015		testing		12		29.944	Liu
18/08/2015		testing		24		29.950	Lv

Lamp number: Wi41/G -189(NIM-05)

Date	Lamp ON time	Activity/Comments (test, alignment, measurement)	Lamp OFF time	Burn time (mins)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
26/01/2014		testing		12	5.7797	29.731	Liu
27/01/2014		testing		12		29.732	Jiang
06/03/2014		testing		12		29.738	Jiang
11/03/2014		testing		12		29.719	Liu
17/08/2015		testing		12		29.711	Liu
18/08/2015		testing		36		29.711	Lv

Lamp number: Wi41/G -1071(NIM-06)

Date	Lamp ON time	Activity/Comments (test, alignment, measurement)	Lamp OFF time	Burn time (mins)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
06/03/2014		testing		12	5.8379	30.103	Jiang
11/03/2014		testing		12		30.099	Liu
17/08/2015		testing		12		30.090	Liu
18/08/2015		testing		24		30.091	Lv

Participant: National Institute of Metrology

NMI: NIM

Date: Aug. 28 ,2015

Signature:

Appendix A.5 Measurement Uncertainty Budget

Lamp Number: Wi41/G -96(NIM-01)

Measurement Round #1:

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp reproducibility(including lamp alignment)	A	0.047
- lamp output fluctuations	A	0.007
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.049
RMS total standard uncertainty:		**0.17**

Lamp Number: Wi41/G -96(NIM-01)

Measurement Round #2:

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp ageing	B	0.018
- lamp reproducibility(including lamp alignment)	A	0.077
- lamp output fluctuations	A	0.002
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.080
RMS total standard uncertainty:		**0.19**

Lamp Number: Wi41/G -152(NIM-02)

Measurement Round #1:

Measurement Parameter	**Uncertainty Type (A or B)**	**Standard Uncertainty in luminous intensity (%)**
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp reproducibility(including lamp alignment)	A	0.062
- lamp output fluctuations	A	0.001
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.063
RMS total standard uncertainty:		**0.18**

Lamp Number: Wi41/G -152(NIM-02)
Measurement Round #2

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp ageing	B	0.024
- lamp reproducibility(including lamp alignment)	A	0.077
- lamp output fluctuations	A	0.001
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.081
RMS total standard uncertainty:		**0.19**

Lamp Number: Wi41/G -164(NIM-03)

Measurement Round #1:

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp reproducibility(including lamp alignment)	A	0.006
- lamp output fluctuations	A	0.002
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.012
RMS total standard uncertainty:		**0.17**

Lamp Number: Wi41/G -164(NIM-03)

Measurement Round #2

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp ageing	B	0.036
- lamp reproducibility(including lamp alignment)	A	0.056
- lamp output fluctuations	A	0.001
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.068
RMS total standard uncertainty:		**0.18**

Lamp Number: Wi41/G -180(NIM-04)

Measurement Round #1:

Measurement Parameter	**Uncertainty Type (A or B)**	**Standard Uncertainty in luminous intensity (%)**
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp reproducibility(including lamp alignment)	A	0.039
- lamp output fluctuations	A	0.002
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.040
RMS total standard uncertainty:		**0.17**

Lamp Number: Wi41/G -180(NIM-04)

Measurement Round #2:

Measurement Parameter	**Uncertainty Type (A or B)**	**Standard Uncertainty in luminous intensity (%)**
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp ageing	B	0.018
- lamp reproducibility(including lamp alignment	A	0.057
- lamp output fluctuations	A	0.001
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.061
RMS total standard uncertainty:		**0.18**

Lamp Number: Wi41/G -189(NIM-05)

Measurement Round #1

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp reproducibility(including lamp alignment)	A	0.046
- lamp output fluctuations	A	0.001
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.047
RMS total standard uncertainty:		**0.17**

Lamp Number: Wi41/G -189(NIM-05)

Measurement Round #2:

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp ageing	B	0.024
- lamp reproducibility(including lamp alignment)	A	0.040
- lamp output fluctuations	A	0.001
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.048
RMS total standard uncertainty:		**0.17**

Lamp Number: Wi41/G -1071(NIM-06)

Measurement Round #1

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp alignment	B	0.065
- lamp reproducibility(including lamp alignment)	A	0.001
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.066
RMS total standard uncertainty:		**0.18**

Lamp Number: Wi41/G -1071(NIM-06)

Measurement Round #2:

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of reference standard	B	0.16
Electrical		
-standard resistor and voltmeter	B	0.03
Photometer		
- spectral mismatch	B	0.01
- linearity	B	0.02
- distance	B	0.03
Environment		
- stray light	B	0.01
RMS total systematic effects:		0.167
Random effects:		
Lamp parameters:		
- lamp ageing	B	0.018
- lamp reproducibility(including lamp alignment)	A	0.081
- lamp output fluctuations	A	0.001
Electrical parameters:		
-lamp current supply fluctuations	B	0.006
Photometer noise	B	0.01
RMS total random effects:		0.083
RMS total standard uncertainty:		**0.19**

Participant: National Institute of Metrology

NMI: NIM

Date: Aug. 28 ,2015

Signature:

Appendix A.6 Measurement Results

Lamp Number: Wi41/G -96(NIM-01)

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
3	1	06/03/2014	5.7940	29.851	2837	253.23	0.049	0.167
4	1	11/03/2014	5.7940	29.841	2837	253.06		

Lamp Number: Wi41/G -152(NIM-02)

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
1	1	26/01/2014	5.8184	30.013*	2829	263.75	0.063	0.167
2	1	27/01/2014	5.8184	30.013*	2829	263.65		
3	1	06/03/2014	5.8184	30.013*	2829	263.16		
4	1	11/03/2014	5.8184	30.014	2829	263.76		

Lamp Number: Wi41/G -164(NIM-03)

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
3		06/03/2014	5.8072	29.781	2841	275.16	0.012	0.167
4		11/03/2014	5.8072	29.780	2841	275.14		

Lamp Number: Wi41/G -180(NIM-04)

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
1	1	26/01/2014	5.8044	29.955*	2839	265.18	0.040	0.167
2	1	27/01/2014	5.8044	29.955*	2839	265.11		
3	1	06/03/2014	5.8044	29.955*	2839	264.99		
4	1	11/03/2014	5.8044	29.949	2839	265.41		

Lamp Number: Wi41/G -189(NIM-05)
Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
1	1	26/01/2014	5.7797	29.731*	2840	269.63	0.047	0.167
2	1	27/01/2014	5.7797	29.732*	2840	269.85		
3	1	06/03/2014	5.7797	29.738*	2840	269.41		
4	1	11/03/2014	5.7797	29.719	2840	269.39		

Lamp Number: Wi41/G -1071(NIM-06)
Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
3	1	06/03/2014	5.8379	30.103	2839	271.40	0.066	0.167
4	1	11/03/2014	5.8379	30.099	2839	271.15		

Specification:
The warm up time for each lamp is ten minutes.
The centre of the lamp is positive, the screw is negative.
The lamp socket has been changed since March 11th. We found that the electrical connection characteristics of the old socket is not good, the characteristics of the new one has been improved. In order to avoid increasing the lamp burning time, we don’t measure too much. The measurement results of voltage in March 11th should be the lamp voltage.
*Measurement with old lamp socket.

Participant: National Institute of Metrology

NMI: NIM

Date: Aug. 28 ,2015

Signature:

Appendix A.6 Measurement Results

Lamp Number: Wi41/G -96(NIM-01)

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
1	1	17/08/2015	5.7940	29.829	2837	252.77	0.080	0.167
2	2	18/08/2015		29.826	2837	252.55		

Lamp Number: Wi41/G -152(NIM-02)

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
1	1	17/08/2015	5.8184	30.019	2829	264.06	0.081	0.167
2	3	18/08/2015		30.020	2829	263.79		

Lamp Number: Wi41/G -164(NIM-03)

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
1	3	17/08/2015	5.8072	29.770	2841	275.61	0.068	0.167
2	3	18/08/2015		29.775	2841	275.59		

Lamp Number: Wi41/G -180(NIM-04)

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
1	1	17/08/2015	5.8044	29.944	2839	265.43	0.061	0.167
2	2	18/08/2015		29.950	2839	265.81		

Lamp Number: Wi41/G -189(NIM-05)

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
1	1	17/08/2015	5.7797	29.711	2840	269.41	0.048	0.167
2	3	18/08/2015		29.711	2840	269.42		

Lamp Number: Wi41/G -1071(NIM-06)

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current (A)	Lamp Voltage (V)	Correlated Colour Temperature (K)	Luminous Intensity (cd)	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
1	1	17/08/2015	5.8379	30.090	2839	271.43	0.083	0.167
2	2	18/08/2015		30.091	2839	271.54		

Specification:

The warm up time for each lamp is ten minutes.

The centre of the lamp is positive, the screw is negative.

Participant: National Institute of Metrology

NMI: NIM

Date: Aug. 28, 2015

Signature:

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>NMIA Report</u>

National Measurement Institute, Australia

Lamp Selection

A set of ten lamps were selected from a stock of Wotan Wi41/G lamps held at NMIA since the 1970s. The lamps were designed with the filament supports below the filament. Each lamp was originally aged shortly after it was purchased. However, in order to select the six lamps to be used for the comparison, the lamps were re-aged for a further period of two to three days each with lamp current, lamp voltage, relative illuminance and ambient temperature recorded every 30 minutes. The lamps were assessed for their ability to maintain luminous intensity as a function of lamp current, lamp voltage, lamp power and filament resistance resulting in a list of lamps with the more stable lamps prioritised over the less stable lamps.

After each lamp had been left to return to ambient temperature, the lamps were then aged for a further period of one hour, including the period during which the lamp was activated, with lamp and ambient parameters recorded at 60 second intervals in order to determine the warm-up period of each lamp. The optimum warm up period (stabilisation time) for each lamp was evaluated by visual analysis of a plot of each of the lamp electrical parameters against the relative illuminance to determine the time required before the plot reached a quasi-linear regime. The worst case time taken for any of the lamps was used for all of the lamps because, once any of the lamps had reached a quasi-stable state, the stability was maintained for the remainder of the ageing period.

The final selection of six lamps was made based on the quality of the black mask on each lamp and the stability of each lamp's base (since many of the lamp bases were poorly connected to the remainder of the lamp envelope).

Optical Setup

For the measurements, the optical path was as follows:

- An absorption cone was mounted with the front edge approximately 50 mm behind the lamp envelope. The cone fully occupied the area behind each lamp visible to the photometer.
- Each lamp was mounted on a carriage on the cast iron photometric bench. A vernier scale on each carriage allowed separation measurement to within ± 0.02 mm in combination with a length scale on the bench. The carriage also provided a receptacle for the kinematic lamp base used with each lamp. The kinematic base allowed adjustment of the height, lateral displacement, longitudinal displacement and angular orientations of each lamp.
- A 16 sided regular stellated aperture, having an approximate dimension of 57 mm between opposing external vertices and shown in Figure 1, was located on the photometric bench at 500 mm in front of the filament mean plane to limit the view of each lamp to an area immediately around the lamp window and within the area of the black mask painted on the lamp.
- A second 16 sided regular stellated aperture having the same dimensions was located

approximately 500 mm in front of the photometer aperture plane to limit the view of the photometer to an area immediately surrounding the first limiting aperture. A double shutter was located immediately in front of this aperture to allow correction for ambient stray light.

- The photometer consisted of a precision aperture of diameter 8.2 mm placed directly in front of the centre of a 15 mm diameter undiffused LMT photometer. The spatial response of the photometer over the central 8 mm diameter area was uniform to within 0.7% of the mean responsivity value. The aperture plane was set at 3.20000 m from the filament mean plane of each lamp. The geometry of measurement corresponded to a solid angle of approximately 5.157 µsr centred on the photometric axis.
- The photometric axis was defined by the line intersecting the centre of the lamp filament and the centre of the sensitive surface of the photometer.

Figure 2 is a schematic diagram of the measurement geometry and a photograph of the approximate bench set up is shown in Figure 3.

Stray light was controlled using a number of components:

- The absorption cone minimised light reflections from behind the lamp using gloss black paint to trap the light.
- The stellated apertures minimised reflections from the inside edges of the aperture back towards the photometric axis, instead predominantly scattering light away from the axis where it was controlled by other means. Although the area of the inside edges is small, the near-grazing incidence geometry means that the reflectance can be significant. The stellated geometry has been found to be an improvement over circular apertures since the cylindrical geometry of the edge of a circular aperture reflects rays originating near the photometric axis back towards that axis.
- Flat black paint was used for optics away from the photometric axis to reduce back-scatter from optical components.
- Black velvet curtains were used to isolate the measurement system from ambient light as much as possible and absorb stray radiation in the visible region inside the measurement system.
- A shutter was used to correct for light leakage into the bench section containing the photometer and other electronic offsets.
- Inter-reflection between the photometer and the shutter plane was largely negated as the reflection factor forms part of the calibration of the photometer when it is calibrated against the working standard lamps.
- Inter-reflection between the baffles was mostly off axis with on axis contributions being negligible. This was also true for reflections between the lamp envelope/mount and the first baffle.
- Light reflected from the bench or the overhead lamp bay was controlled by the limited view allowed by the baffles.

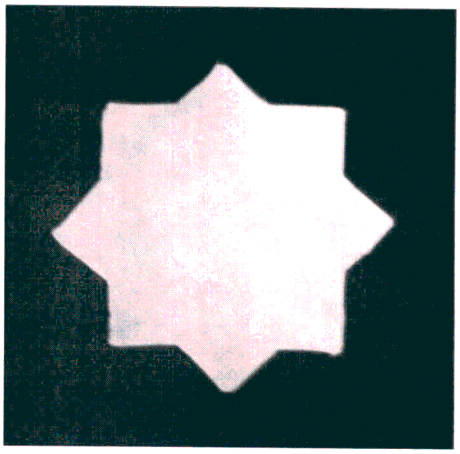


Figure 1 Stellated Aperture Pattern

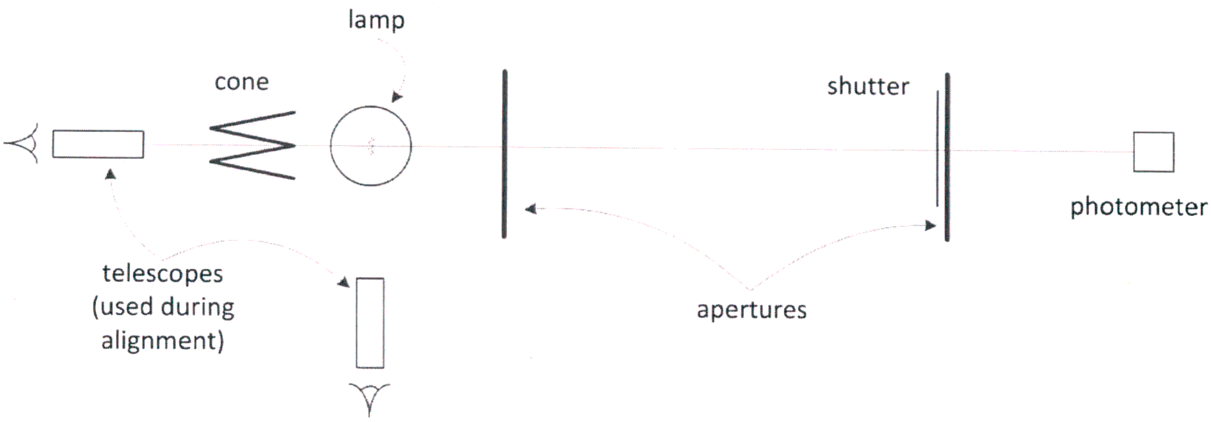


Figure 2 Schematic diagram of measurement setup

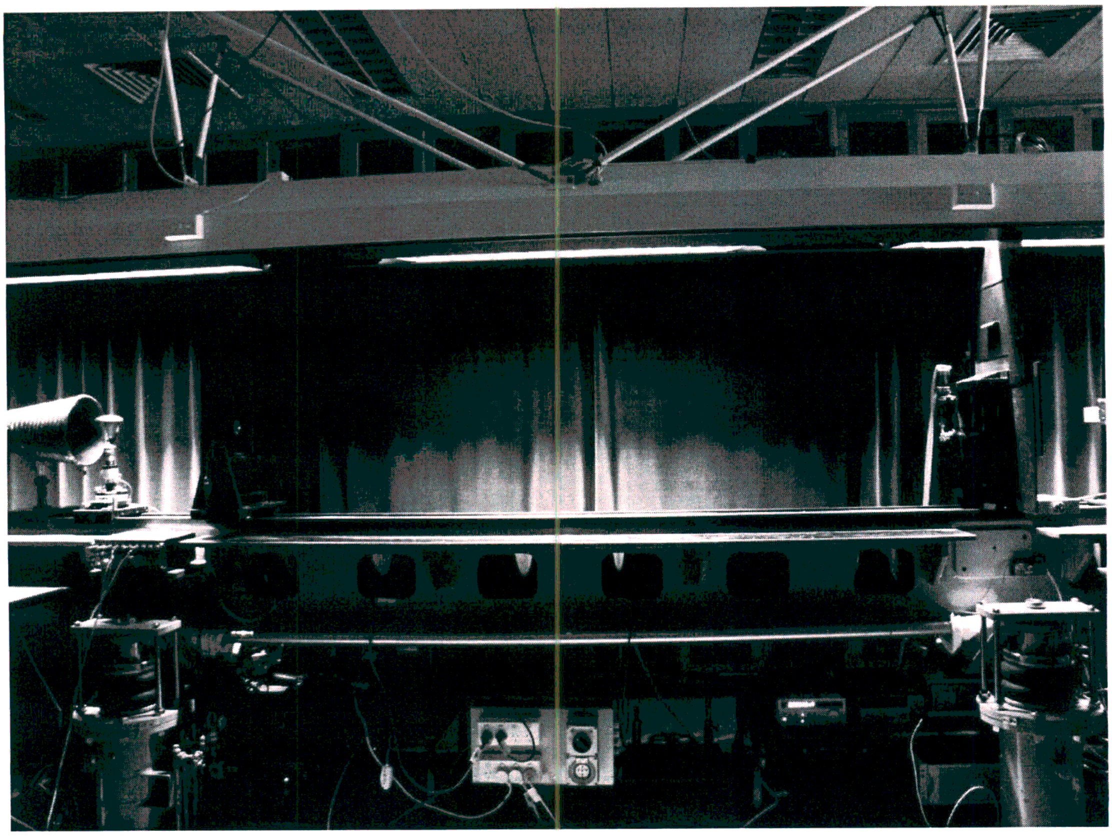


Figure 3 Photometric Bench Set Up

Alignment of Lamps

Each lamp was aligned in accordance with the recommendations of the CCPR-K3.2014 protocol, section 4, with the filament mean plane set at 3.20000 m from the photometer reference plane when the filament was at room temperature.

Each lamp was aligned by use of two bench telescopes, one set to view along the photometric axis and the other set orthogonally to the axis. The axial telescope provided facility for alignment of the lamp filament centre with that of the photometric axis for each lamp (for height and lateral displacement). The vernier mounted telescope oriented orthogonally to the photometric axis provided facility for establishing the angular orientation of each lamp following the recommendations of the protocol.

An alignment jig was used to set the orthogonal telescope position to 3.20000 m from the photometer. For each lamp, the lamp carriage was then positioned so the filament was centred on the graticule of this telescope. A second jig was used at the photometer aperture position to enable the use of a calibrated inside micrometer to validate the photometric bench length scale. The telescope alignment procedure and scale validation was performed for each set of measurements. The procedure allowed the physical distance between the filament mean plane and the photometer aperture position to be set to within ± 0.10 mm. The angular orientation of the lamps was limited to within ± 0.2°, subject to the flatness of filament construction.

Operating Parameters

Each lamp was run on direct current with positive polarity to the centre contact on the lamp base.

The current used for each lamp was determined by a series of spectral measurements covering the CCT spectral range to determine the value of current which delivers a lamp CCT closest to 2856 K.

On each use of the lamps, the lamp power supply was activated and checked before the lamps were connected and then the lamp current was slowly increased to the prescribed value over a period of approximately 60 seconds.

The optimum warm up time for the lamps was determined to be 19 minutes from reaching full prescribed current and measurements were performed in a period of 60 seconds following the warm up period. Based on the observed stability of the lamps, very little difference in luminous intensity would occur if the measurement period was extended to a few minutes.

During measurements the lamp illuminance values recorded were corrected for deviations in applied current using relationships determined during the short term ageing of each lamp.

At the end of each measurement cycle the lamp current was reduced to zero over a period of approximately 30 seconds before the lamp was disconnected from the power supply and the power supply deactivated.

The laboratory ambient temperature was monitored using a calibrated temperature logger with a sensor located immediately over the photometer position. The laboratory temperature was maintained between 19.9 °C and 22.0 °C for all measurements.

Laboratory humidity was 50% ± 5% RH during measurements.

Traceability

The normalised spectral responsivity of the photometer is traceable to the NMIA cryogenic radiometer and bolometers via spectral responsivity transfer from working standard Hamamatsu plane silicon photodiodes, with calibration over the wavelength range between 250 nm and 1000 nm. The relative responsivity transfer was last performed in August 2011 showing minimal changes since the photometer was first calibrated by NMIA (then CSIRO NML) in 1996.

The geometry specific absolute calibration of the photometer is traceable to the NMIA cryogenic radiometer and bolometers via a 4-element transmission trap utilising a stabilised source with a number of selected filter combinations to limit the spectral bandwidth whilst matching the physical geometry and coherence state of the NMIA working standard lamps as closely as possible. A precision aperture, calibrated using the NMIA optical aperture area characterisation facility, is used in conjunction with the trap and photometer to define the area component of the calibration. The calibration of the photometer is immediately transferred to four working standard Phillips 6369 lamps operating at 2856 K CCT, each with lamp histories of more than 25 years showing a worst case drift of -0.45% in 26 years with the lamp being run on over 460 separate occasions during this time. The best of the four lamps shows a drift of less than 0.009% in 26 years. The absolute transfers were last performed in July 2012.

The spectral distribution (correlated colour temperature) of each lamp is traceable to the NMIA scale of spectral irradiance as presented in the most recent CCPR-K1.a.

Lamp voltage is traceable to voltage standards maintained by the NMIA Low Frequency Electrical Project.

Lamp current is traceable to voltage and to resistance standards maintained by the NMIA Impedance Project.

The ambient temperature measurements were traceable to temperature standards maintained by the NMIA Temperature Project.

The laboratory humidity measurements were performed using a Vaisala probe whose calibration status is maintained by the NMIA Mass and Related Quantities Project.

Dimensional measurements were traceable to the dimensional standards maintained by the NMIA Length Project.

Uncertainty Evaluation

The uncertainty of calibration for each measurement was evaluated with consideration of the CCPR-K3.2014 protocol and the current (more comprehensive) list of uncertainty components maintained at NMIA. A typical resultant uncertainty evaluation is listed here:

Systematic Effects:			
	Calibration of Working Standards	Uncertainty Type (A or B)	Standard Uncertainty (%)
	Reference Calibration	A & B	0.030
	Aperture Area	B	0.020
	Trap Area Correction	B	0.005
	Trap Loss Correction	A	0.001
	Spectral Variation	A	0.090
	Aperture Lateral Position	B	0.000
	Thermal variation	B	0.000
	Out of band response	B	0.000
	Reference Linearity	B	0.055
	Reference Ageing	B	0.030
	Reference Position	B	0.005
	Transfer 1	A	0.004
	Distance 1	B	0.005
	Current setting 1	B	0.063
	V(lambda) mismatch	B	0.001
	Non-linearity	B	0.012
	Reference Drift	B	0.000

	R Instrument resolution	B	0.003
	Baffle Effects	B	0.000
	Test Lamp orientation	B	0.000
	Temperature effects	B	0.010
	Area Correction	B	0.000
	Cumulative Total for Working Standards	A & B	**0.133**
	Electrical		
	Resistor Calibration	A & B	0.002
	Voltmeter Calibration	A & B	0.019
	Photometer		
	Spectral Mismatch / Fluorescence	B	0.023
	Linearity	B	0.002
	Lamp envelope refractive index correction (Optical vs Physical separation)	B	0.031
	Lamp envelope diffusion effect on effective calibration plane	B	0.000
	Thermal effects (localised reference lamp heat affecting separation on bench)	B	0.000
	Thermal effects (filament expansion affecting filament position within reference lamp)	B	0.000
	Thermal effects (filament expansion affecting filament position within test lamp)	B	0.013
	Area Correction	B	0.033
	Ageing	B	0.036
	Alignment of references	B	0.000
	Reference agreement	A	0.030
	Environment		
	Stray light (Room light leakage)	B	0.000
	Stray light (Baffle edge reflection)	B	0.002
	Stray light (Baffle inter-reflection)	B	0.000
	Temperature	B	0.019
	RMS Total Systematic Effects		**0.153**
Random Effects:			
	Transfer to Intercomparison Lamps		
	Separation resolution (reference lamp to photometer)	B	0.000
	Separation stability (reference lamp to photometer) (mount variability)	B	0.002
	Separation resolution (Photometer to test lamp)	B	0.000
	Separation stability (Photometer to test lamp) (mount variability)	B	0.002
	Intercomparison lamp alignment	B	0.031
	Cumulative total for transfer to intercomparison lamps	B	**0.031**

	Lamp parameters		
	Reproducibility	A	0.006
	Electrical parameters - see reproducibility		
	Photometer noise - see reproducibility		
	RMS Total Random Effects		**0.032**

Participant: Peter Manson

NMI: NMI Australia

Date: 1 September 2015

Signature:

`Appendix A.6 Measurement Results

Lamp Number: 288 SI4

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	26 Feb 2014 15:09	5.786	31.6578	301.452	0.093	0.153
2	20	28 Feb 2014 12:00	5.786	31.6493	301.277	0.105	0.153
3	20	03 Mar 2014 15:57	5.786	31.7098	301.928	0.082	0.153

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	1 Apr 2015 15:18	5.786	31.6815	301.205	0.100	0.150
2	20	6 May 2015 16:09	5.786	31.6606	301.619	0.077	0.153
3	20	8 May 2015 14:29	5.786	31.6622	301.593	0.077	0.150

The random/systematic labels in this table are those related to the measurements within the particular round of the measurements. If the systematic factors change between the measurement rounds, this information should be indicated separately.

Participant: Peter Manson

NMI: NMI Australia

Date: 31 August 2015

Signature:

Appendix A.6 Measurement Results

Lamp Number: 306 S15

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	26 Feb 2014 15:52	5.858	32.0704	308.299	0.029	0.153
2	20	28 Feb 2014 11:26	5.858	32.0855	308.703	0.029	0.153
3	20	03 Mar 2014 16:34	5.858	32.0788	308.495	0.029	0.153

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	1 Apr 2015 16:01	5.858	32.0955	309.078	0.028	0.150
2	20	6 May 2015 15:35	5.858	32.0989	308.340	0.029	0.153
3	20	8 May 2015 15:05	5.858	32.0944	308.370	0.028	0.150

The random/systematic labels in this table are those related to the measurements within the particular round of the measurements. If the systematic factors change between the measurement rounds, this information should be indicated separately.

Participant: Peter Manson

NMI: NMI Australia

Date: 31 August 2015

Signature: [signature]

CCPR-K3.2013: Luminous Intensity

Appendix A.6 Measurement Results

Lamp Number: 318 SI2

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	26 Feb 2014 16:30	5.781	31.7198	305.775	0.032	0.153
2	20	28 Feb 2014 10:52	5.781	31.7200	305.921	0.032	0.153
3	20	03 Mar 2014 17:02	5.781	31.7250	305.500	0.062	0.153

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	1 Apr 2015 16:32	5.781	31.7345	306.166	0.031	0.150
2	20	6 May 2015 14:40	5.781	31.7396	305.943	0.031	0.153
3	20	8 May 2015 15:35	5.781	31.7327	305.429	0.031	0.150

The random/systematic labels in this table are those related to the measurements within the particular round of the measurements. If the systematic factors change between the measurement rounds, this information should be indicated separately.

Participant: Peter Manson

NMI: NMI Australia

Date: 31 August 2015

Signature:

Appendix A.6 Measurement Results

Lamp Number: 350 LI3

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	26 Feb 2014 17:02	5.794	31.7390	297.712	0.032	0.153
2	20	27 Feb 2014 18:02	5.794	31.7364	299.013	0.032	0.153
3	20	04 Mar 2014 15:58	5.794	31.7489	298.163	0.035	0.153
4	20	04 Mar 2014 17:35	5.794	31.7408	298.888	0.033	0.153

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	1 April 2015 17:01	5.794	31.7493	298.577	0.033	0.150
2	20	5 May 2015 15:14	5.794	31.7542	299.078	0.032	0.153
3	20	8 May 2015 16:02	5.794	31.7500	298.392	0.032	0.150

The random/systematic labels in this table are those related to the measurements within the particular round of the measurements. If the systematic factors change between the measurement rounds, this information should be indicated separately.

Participant: Peter Manson

NMI: NMI Australia

Date: 31 August 2015

Signature: P. Manson

CCPR-K3.2013: Luminous Intensity

Appendix A.6 Measurement Results

Lamp Number: S7

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	26 Feb 2014 18:43	5.780	31.7229	298.848	0.015	0.153
2	20	27 Feb 2014 16:46	5.780	31.7284	298.640	0.016	0.153
3	20	04 Mar 2014 17:03	5.780	31.7213	298.776	0.016	0.153

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	1 Apr 2015 17:32	5.780	31.7304	299.062	0.014	0.150
2	20	5 May 2015 14:42	5.780	31.7481	298.467	0.014	0.153
3	20	8 May 2015 16:30	5.780	31.7302	298.620	0.014	0.150

The random/systematic labels in this table are those related to the measurements within the particular round of the measurements. If the systematic factors change between the measurement rounds, this information should be indicated separately.

Participant: Peter Manson

NMI: NMI Australia

Date: 31 August 2015

Signature: P. Manson

Appendix A.6 Measurement Results

Lamp Number: S14

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	26 Feb 2014 17:33	5.816	31.7462	298.853	0.140	0.153
2	20	27 Feb 2014 17:24	5.816	31.7542	298.737	0.140	0.153
3	20	04 Mar 2014 16:30	5.816	31.7539	297.767	0.140	0.153

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp Current / A	Lamp Voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	20	1 Apr 2015 18:02	5.816	31.7683	300.436	0.140	0.150
2	20	5 May 2015 14:07	5.816	31.7898	299.771	0.140	0.153
3	20	8 May 2015 17:02	5.816	31.7654	299.622	0.140	0.150

The random/systematic labels in this table are those related to the measurements within the particular round of the measurements. If the systematic factors change between the measurement rounds, this information should be indicated separately.

Participant: Peter Manson

NMI: NMI Australia

Date: 31 August 2015

Signature:

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>NMIJ Report</u>

TO: Dr. Arnold A. Gaertner
Measurement Science and Standards
Building M-36, Room 115
National Research Council of Canada
1200 Montreal Road
Ottawa, Ontario, Canada K1A 0R6

FAX: 613-952-1394
Email: Arnold.Gaertner@nrc-cnrc.gc.ca

FROM: Kenichi Kinoshita
Photometry and Radiometry Research Group,
Research Institute for Physical Measurement,
National Metrology Institute of Japan,
National Institute of Advanced Industrial Science and Technology,
Central 3-1, 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563 Japan
TEL: +81 29 861 4082
FAX: +81 29 861 4860
E-Mail: kenichi.kinoshita@aist.go.jp

CCPR-K3.2014 Luminous Intensity
Final measurement results

Appendix A.3 Description of the measurement facility

Description of measurement geometry:

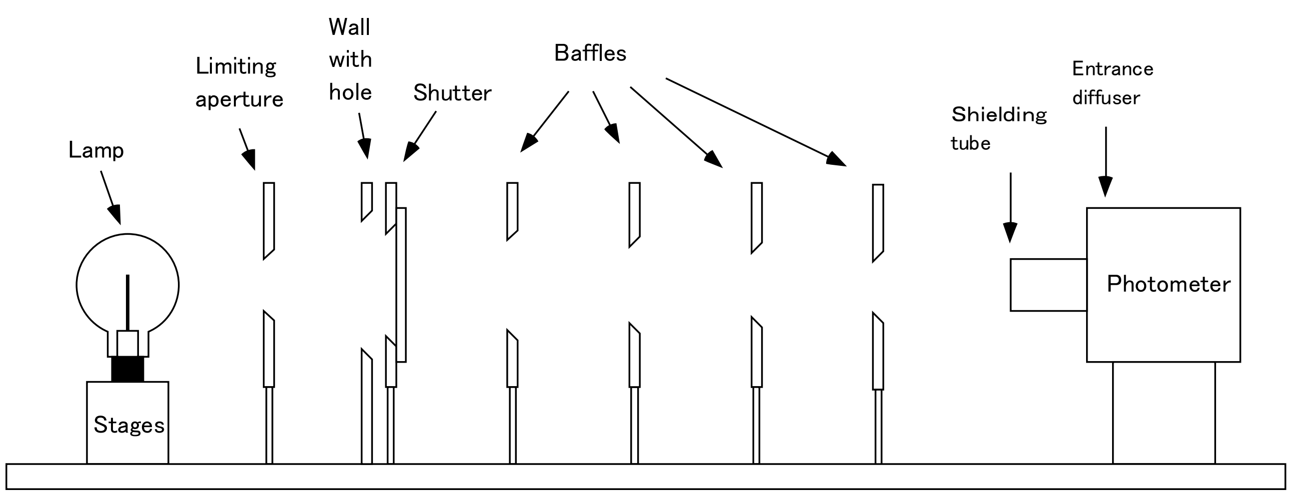
In the calibration process at NMIJ, luminous intensity of a lamp is calibrated by a comparison with a group of luminous intensity standard lamps. During measurement, a lamp and a photometer are located on a photometric bench. A wall lying midway on the photometric bench separates the lamp area and the measurement area. A hole on the wall allows the light from the lamp to go to the measurement area where the photometer is placed. Baffles and a shutter are also placed between the lamp and the photometer. The number of baffles is four. In the measurement of an Osram Wi41/G lamp, a limiting aperture is used additionally to reduce stray light and to measure the light through the rectangular mask of the lamp only. The measurement geometry is shown in Fig. 1.

The lamp alignment system consists of a lamp alignment stage and alignment apparatus such as a laser and cameras. 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. The lamp alignment procedure is described later.

The position of the photometer is determined so that the laser beam that coincides with the optical axis comes to the center of the shielding tube of the photometer.

The sizes and the distances of the limiting aperture, the hole on the wall, the baffles, and the shutter are shown in Fig. 1.

The distance between the center of the lamp filament and the entrance diffuser of the photometer (reference plane) is 2.7 m. The diameter of the entrance diffuser of the photometer is 40 mm. Therefore, the solid angle formed by the entrance diffuser of the photometer is about 1.7×10^{-4} rad.



0.0	0.50	1.08	1.24	1.50	1.77	2.01	2.39	2.60	2.70	Distance [m]
	75	250	200	150	125	100	75	50	40	Diameter [mm]

Fig. 1. Measurement geometry at NMIJ.

Description of measurement procedures:

Luminous intensity of a lamp is calibrated by a comparison with a group of luminous intensity standard lamps. For CCPR-K3 comparison, six traveling lamps (DUT_1, DUT_2, ..., and DUT_6) 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, DUT_1, ..., DUT_6, DUT_6, ..., DUT_1, S_B, S_A). In each measurement, 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 procedure. The first half of the measurement sequence (S_A, S_B, DUT_1, ..., DUT_6) is called "Go" measurement, and the latter half (DUT_6, ..., DUT_1, S_B, S_A) is "Return" measurement, respectively. The light from each lamp is detected with the photometer aligned on the photometric bench. Output signals from the photometer are measured with a 8.5-digit digital multimeter and collected by a computer. The average of the output signals for each lamp from two measurement sequences "Go" and "Return" is used for the following calculation of luminous intensity.

The luminous intensity of a traveling lamp I_i (i=1 to 6) is determined as the average of two values derived separately from the calculations based on the individual luminous intensity of the standard lamps.
The value to be calculated from one standard lamp for a traveling lamp is the product of three quantities, i.e., the luminous intensity of the standard lamp, the ratio of the output signal for the traveling lamp to that for the standard lamp, and the color correction factor. Therefore, the luminous intensity of the traveling lamp is obtained in the following equation.

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

where I_i is the luminous intensity of the i-th traveling lamp, I_a and I_b are the luminous intensity of the standard lamps S_A and S_B, V_i, V_a, and V_b are the output signals of the i-th traveling lamp, the standard lamps S_A and S_B, and k_{ai} and k_{bi} are the color correction factors between the i-th traveling lamp and S_A and S_B, respectively. As mentioned above, the output signals used here are the averages of the measurement sequences "Go" and "Return" for the respective lamps.

*) In this final measurement report, the data of the sixth lamp (No. 69) is excluded because of the large discrepancy in luminous intensity between the first round measurement and the second round measurement measured at NMIJ, which implies unexpected instability of this lamp.

Make and type of the photometer (or equivalent):

The photometer used for the calibration is manufactured by Kouno Kouki Sangyou KK, which has closed down its business already. The photometer consists of an 100 mm diameter integrating sphere with an entrance diffuser (matte opal glass) and three filtered Si photodiodes; B(blue), Y(yellow), and R(red) detectors. Spectral responsivity of the Y detector is approximated to $V(\lambda)$ whose $V(\lambda)$ mismatch index f_1' is 2.11. The output signal from the Y detector is used for the calibration of luminous intensity. 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 to be measured.

Operating conditions of the lamps:

The lamp filament is observed with two cameras. One camera is located along with the X axis (optical axis) to see the rear view of the filament, and the other is located along with the Y axis to see the side view. The coordinate system is taken to agree with the description in the protocol. Each view has cross hairs pre-aligned to coincide with the origin of the coordinate system and the coordinate axes. The lamp alignment is made in such a way that the filament position comes in accordance with these cross hairs.

The alignment procedure for the Osram Wi41/G lamp is as follows.

The rotation about the Z axis (θ_Z) is adjusted so that the shape of the filament in the side view becomes narrowest. Care must be taken when aligning the traveling lamps #58 and #69, because the wires that compose the filament of both lamps are slightly uneven and not formed the single plane. For these lamps, the angle about the Z axis (θ_Z) is adjusted so that the widths of the upper half and lower half of the filament is balanced (see Fig. 2).

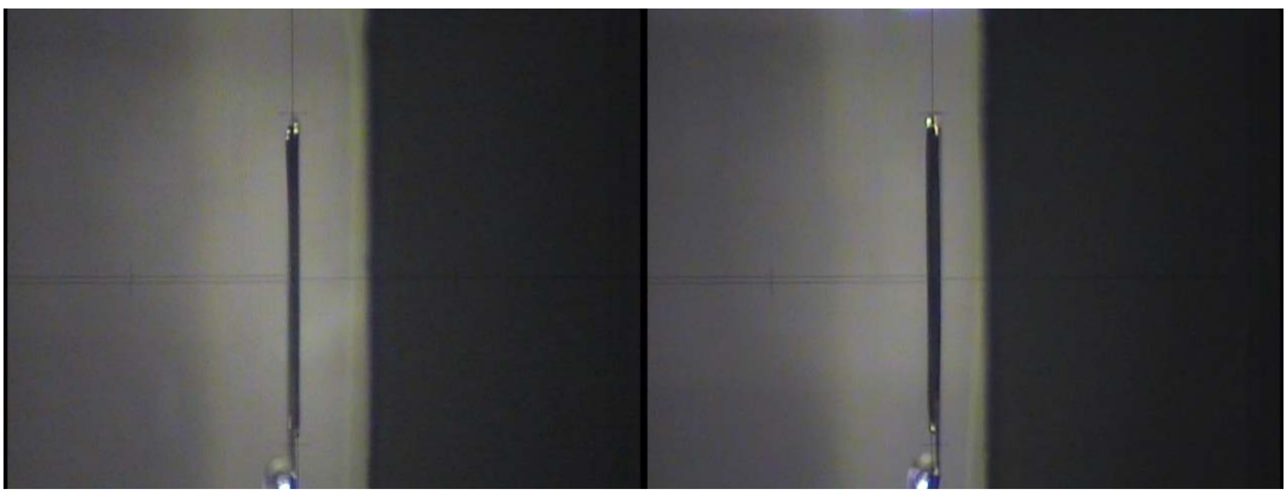


Fig. 2. Side views of the lamp #58(left) and #69(right).

The rotation about the X (θ_X) axis is adjusted so that the rectangular shape of the filament in the rear view stands upright.

Then the rotation about the Y axis (θ_Y) is adjusted so that the filament in the side view coincides with the vertical axis. Care must also be taken when aligning the traveling lamps #58 and #69 because the shapes of the filaments seem slightly curved. For these lamps, the angle about the Y axis is adjusted so that the line fitted to the shape of the filament coincides to the Y axis.

The height of the filament is adjusted so that the half height of the filament coincides with the horizontal line of the cross hair that is in accordance with the origin of the coordinate system.

The position of the filament along with the Y-axis is adjusted so that the origin of the coordinate system comes to the center between the 6th and 7th wires of the filament. The wires are numbered as shown in Fig. 3.

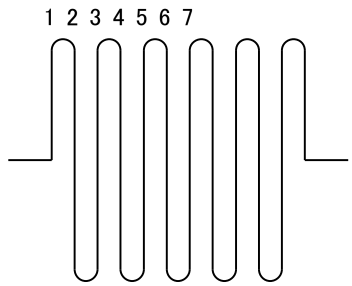


Fig. 3. Numbering filament wires.

The position of the filament along with the X-axis is adjusted so that the center of the filament coincides with the origin of the coordinate system.

The filament is aligned at room temperature.

No special jig for alignment is used.

The size and position of the limiting aperture are described in Fig. 1.

For all the traveling lamps, electrical polarity is defined so that the negative pole is connected to the center of the socket when electrical current is supplied. The measured lamp current and voltage for each traveling lamp are as follows. The lamps are operated with the constant current mode.

#37	5.7563 A	29.0689 V
#40	5.7943 A	29.5493 V
#51	5.7362 A	29.2641 V
#52	5.7646 A	29.1673 V
#58	5.6101 A	29.9704 V
#69	5.6198 A	29.9225 V

When turning on a traveling lamp, electrical current is increased gradually from zero to the fixed value in two minutes. After the lamp current reaches the fixed value, the warm-up time of 13 minutes is applied before measurement.

The distribution temperature of each lamp is as follows.

#37	2800 K
#40	2800 K
#51	2800 K
#52	2800 K
#58	2800 K
#69	2800 K

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

A schematic diagram of the luminous intensity calibration facilities is shown in Fig. 4. A lamp voltage is measured by a 8.5-digit digital multimeter. A lamp current is determined by measuring the voltage between the terminal 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 multimeters to stabilize the lamp voltage (constant voltage mode, for NMIJ standard lamps) or current (constant current mode, for travelling lamps: Osram Wi41/G). An amplified output of the photometer is measured by another 8.5-digit digital multimeter.

During the calibration, laboratory conditions are controlled as follows.

Temperature 23.0 °C ± 2.0 °C

Humidity 50 % ± 20 %

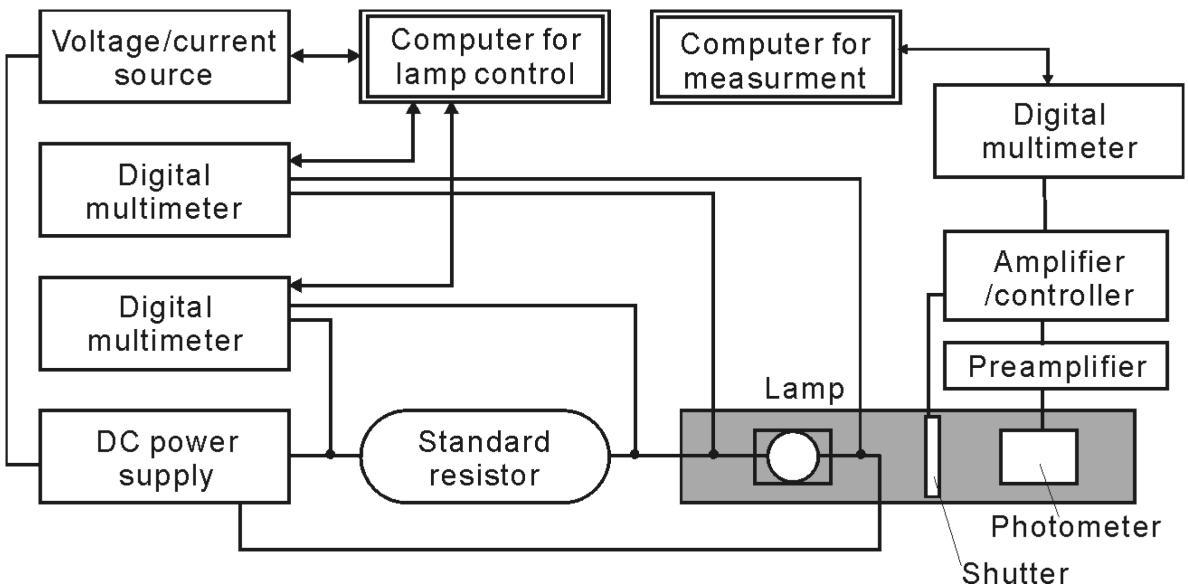


Fig. 4. Schematic diagram of measurement instruments.

Laboratory transfer standards used:

The luminous intensity scale of NMIJ is maintained with four standard lamps. The type of the standard lamps is Toshiba 55 V-330 W coil-M-type luminous intensity standard lamp. The traceability diagram is shown in Fig. 5. Two lamps are used as the luminous intensity standard lamps and another two are used as the luminous intensity working standard lamps according to Fig. 5. In this comparison, the traveling lamps are directly calibrated with the luminous intensity standard lamps.

The date of last realization of the NMIJ primary scale is Jan. 30th, 1998. The uncertainty budget is shown in Table 1.

Table 1: Uncertainty budget for the realization of luminous intensity at NMIJ.

Source of uncertainty	**Uncertainty Type (A or B)**	**Standard Uncertainty in luminous intensity (%)**
Spectral responsivity of the silicon photodiode measured with the cryogenic radiometer	B	0.05
Illuminance responsivity of the standard photometer with respect to the spectral responsivity of the silicon photodiode	B	0.20
Measurement of the distance between the primary standard lamp and the transfer detector	B	0.05
Responsivity change of the transfer detector by room temperature fluctuation	B	0.10
Setting of the luminous intensity primary standard lamp	B	0.10
Aperture area	B	0.015
Total standard uncertainty		0.255

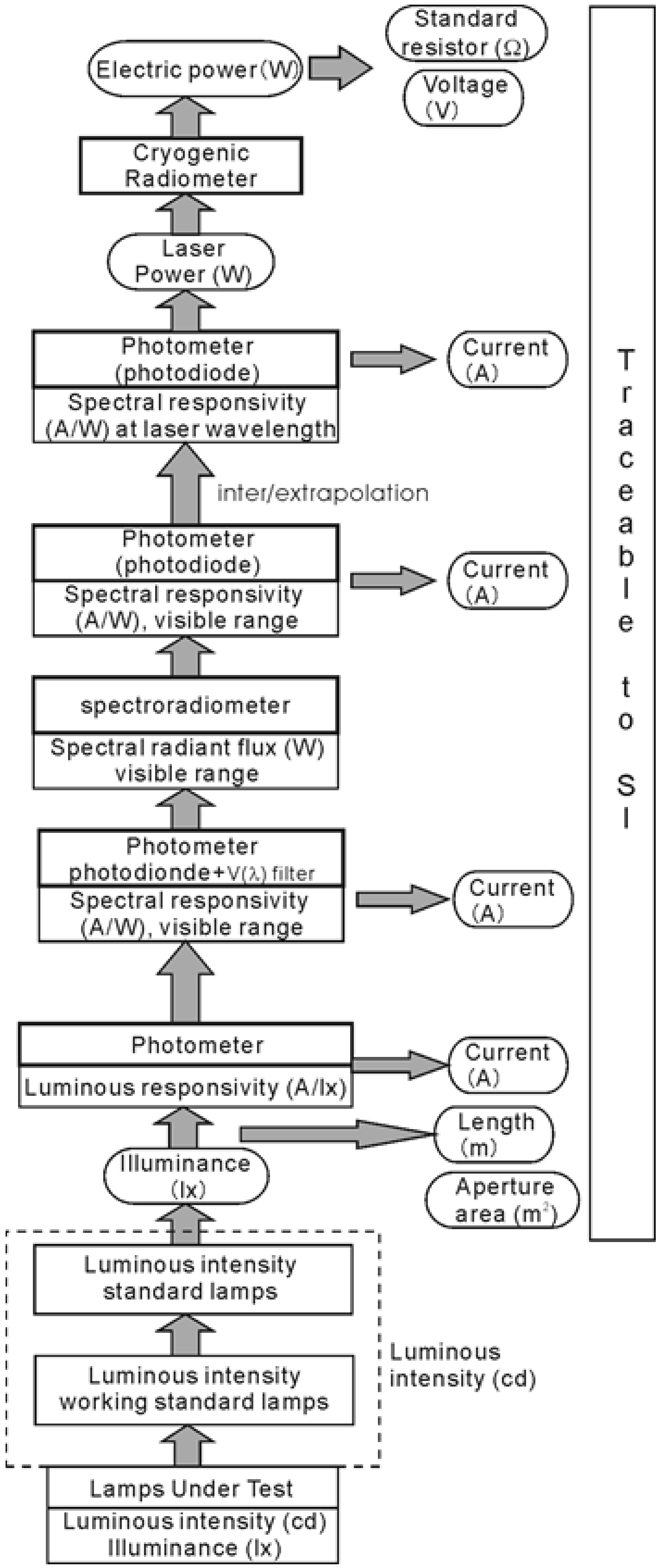


Fig.5. Traceability diagram

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.4 Record of lamp operating time

Lamp number: 37

Date	**Lamp ON time**	**Activity/Comments (test, alignment, measurement)**	**Lamp OFF time**	**Burn time (hrs)**	**Lamp Current (amperes)**	**Lamp Voltage (volts)**	**Operator initials**
Feb. 2nd 2014	13:13:38	**measurement**	13:27:00	0.2228	5.7563	29.0706	K.K
Feb. 2nd 2014	23:25:16	**measurement**	23:38:37	0.2222	5.7563	29.0692	K.K
Feb. 8th 2014	11:22:58	**measurement**	11:36:14	0.2211	5.7563	29.0697	K.K
Feb. 8th 2014	19:28:53	**measurement**	19:42:07	0.2203	5.7563	29.0689	K.K
Mar. 21st 2015	11:31:17	**measurement**	11:44:35	0.2214	5.7563	29.0644	K.K
Mar. 21st 2015	22:44:55	**measurement**	22:58:10	0.2208	5.7563	29.0621	K.K
Mar. 27nd 2015	9:42:07	**measurement**	9:55:16	0.2194	5.7563	29.0638	K.K
Mar. 27nd 2015	16:24:27	**measurement**	16:37:36	0.2192	5.7563	29.0612	K.K

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.4 Record of lamp operating time

Lamp number: 40

Date	Lamp ON time	Activity/Comments (test, alignment, measurement)	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
Feb. 2nd 2014	14:27:20	**measurement**	14:40:41	0.2225	5.7943	29.5502	K.K
Feb. 2nd 2014	22:49:30	**measurement**	23:02:46	0.2214	5.7943	29.5505	K.K
Feb. 8th 2014	11:55:55	**measurement**	12:09:16	0.2222	5.7943	29.5496	K.K
Feb. 8th 2014	19:00:47	**measurement**	19:14:08	0.2225	5.7943	29.5493	K.K
Mar. 21st 2015	12:01:05	**measurement**	12:14:21	0.2214	5.7943	29.5431	K.K
Mar. 21st 2015	22:16:42	**measurement**	22:29:56	0.2203	5.7943	29.5438	K.K
Mar. 27nd 2015	10:09:36	**measurement**	10:22:45	0.2192	5.7943	29.5436	K.K
Mar. 27nd 2015	15:58:33	**measurement**	16:11:40	0.2189	5.7943	29.5419	K.K

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.4 Record of lamp operating time

Lamp number: 51

Date	Lamp ON time	Activity/Comments (test, alignment, measurement)	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
Feb. 2nd 2014	15:14:04	**measurement**	15:27:23	0.2217	5.7362	29.2654	K.K
Feb. 2nd 2014	22:19:45	**measurement**	22:33:02	0.2214	5.7362	29.2646	K.K
Feb. 8th 2014	12:31:51	**measurement**	12:45:09	0.2214	5.7362	29.2659	K.K
Feb. 8th 2014	18:30:51	**measurement**	18:44:08	0.2214	5.7362	29.2641	K.K
Mar. 21st 2015	12:33:18	**measurement**	12:46:34	0.2214	5.7362	29.2613	K.K
Mar. 21st 2015	17:13:33	**measurement**	17:26:49	0.2211	5.7362	29.2615	K.K
Mar. 27nd 2015	10:36:01	**measurement**	10:49:08	0.2189	5.7362	29.2617	K.K
Mar. 27nd 2015	15:32:36	**measurement**	15:45:47	0.2197	5.7362	29.2600	K.K

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.4 Record of lamp operating time

Lamp number: 52

Date	Lamp ON time	Activity/Comments (test, alignment, measurement)	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
Feb. 2nd 2014	16:34:32	**measurement**	16:47:54	0.2225	5.7646	29.1680	K.K
Feb. 2nd 2014	21:40:23	**measurement**	21:53:41	0.2217	5.7646	29.1676	K.K
Feb. 8th 2014	13:09:22	**measurement**	13:22:39	0.2214	5.7646	29.1659	K.K
Feb. 8th 2014	18:00:15	**measurement**	18:13:30	0.2208	5.7646	29.1673	K.K
Mar. 21st 2015	13:05:08	**measurement**	13:18:26	0.2214	5.7646	29.1598	K.K
Mar. 21st 2015	16:40:58	**measurement**	16:54:13	0.2206	5.7646	29.1602	K.K
Mar. 27nd 2015	11:04:13	**measurement**	11:17:24	0.2194	5.7646	29.1595	K.K
Mar. 27nd 2015	15:07:22	**measurement**	15:20:35	0.2203	5.7646	29.1612	K.K

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.4 Record of lamp operating time

Lamp number: 58

Date	**Lamp ON time**	**Activity/Comments (test, alignment, measurement)**	**Lamp OFF time**	**Burn time (hrs)**	**Lamp Current (amperes)**	**Lamp Voltage (volts)**	**Operator initials**
Feb. 2nd 2014	17:25:50	**measurement**	17:39:06	0.2211	5.6101	29.9692	K.K
Feb. 2nd 2014	21:02:38	**measurement**	21:15:55	0.2211	5.6101	29.9689	K.K
Feb. 8th 2014	15:15:35	**measurement**	15:28:51	0.2211	5.6101	29.9699	K.K
Feb. 8th 2014	17:17:16	**measurement**	17:30:32	0.2214	5.6101	29.9704	K.K
Mar. 21st 2015	13:37:09	**measurement**	13:50:25	0.2214	5.6101	29.9651	K.K
Mar. 21st 2015	16:05:08	**measurement**	16:18:23	0.2208	5.6101	29.9652	K.K
Mar. 27nd 2015	11:34:30	**measurement**	11:47:43	0.2200	5.6101	29.9643	K.K
Mar. 27nd 2015	14:37:19	**measurement**	14:50:31	0.2203	5.6101	29.9633	K.K

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.4 Record of lamp operating time

Lamp number: 69

Date	**Lamp ON time**	**Activity/Comments (test, alignment, measurement)**	**Lamp OFF time**	**Burn time (hrs)**	**Lamp Current (amperes)**	**Lamp Voltage (volts)**	**Operator initials**
Feb. 2nd	18:05:18	**measurement**	18:18:35	0.2217	5.6198	29.9220	K.K
Feb 2nd	20:16:21	**measurement**	20:29:40	0.2219	5.6198	29.9204	K.K
Feb. 8th	15:52:21	**measurement**	16:05:37	0.2208	5.6198	29.9202	K.K
Feb 8th	16:48:29	**measurement**	17:01:44	0.2211	5.6198	29.9225	K.K
Mar. 21st 2015	14:13:10	**measurement**	14:26:27	0.2214	5.6198	29.9150	K.K
Mar. 21st 2015	15:33:20	**measurement**	15:46:35	0.2208	5.6198	29.9165	K.K
Mar. 27nd 2015	11:59:47	**measurement**	12:12:56	0.2194	5.6198	29.9152	K.K
Mar. 27nd 2015	12:26:52	**measurement**	12:40:00	0.2189	5.6198	29.9166	K.K

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Jul. 1, 2016

Signature: 木下健一

Appendix A.5 Sample Measurement Uncertainty Budget

Measurement Parameter	**Uncertainty Type (A or B)**	**Standard Uncertainty in luminous intensity (%)**
Systematic effects:		
Calibration of working standards		
- Spectral responsivity of the silicon photodiode measured with the cryogenic radiometer	B	0.05
- Illuminance responsivity of the standard photometer with respect to the spectral responsivity of the silicon photodiode	B	0.20
- Measurement of the distance between the primary standard lamp and the transfer detector	B	0.05
- Responsivity change of the transfer detector by room temperature fluctuation	B	0.10
- Setting of the luminous intensity primary standard lamp	B	0.10
- Aperture area	B	0.015
Electrical		
- standard resistor		negligible
- digital multimter	B	0.01
Photometer		
- spectral mismatch		negligible
- linearity		negligible
- distance	B	0.02
Environment		
- stray light		negligible
- temperature / humidity ?		included in (*)
RMS total systematic effects:		0.256
Random effects:		
Lamp parameters:		
- lamp ageing	B	0.11
- lamp alignment (*)	B	0.06
- lamp reproducibility		included in (*)
- lamp output fluctuations	B	0.02
Electrical parameters:		
- power supply fluctuations		included in (*)
Photometer noise		included in (*)
(Measurement Set standard deviation of mean)		
RMS total random effects:		0.127
RMS total standard uncertainty:		0.29

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Dear Dr. Gaertner,

The following equations are the physical model of uncertainty of luminous intensity at NMIJ.

$$I_1 = \frac{K_m (d_1 + \Delta d_1)^2}{A} \frac{V_0}{G} \frac{\int_{\lambda_1}^{\lambda_2} \Phi_{e,\lambda}(\lambda)\ V(\lambda)\ d\lambda}{\int_{\lambda_1}^{\lambda_2} \Phi_{e,\lambda}(\lambda)\ s_e(\lambda)\ d\lambda} (1 + c_t)\ (1 + c_1) \quad (1)$$

$$I_2 = I_1\ k_c \frac{V_2}{V_1} \frac{(d_2 + \Delta d_2)^2}{d_2{}^2} (1 + c_i)\ (1 + c_a)\ (1 + c_2)\ (1 + c_3) \quad (2)$$

Equation (1) is the model to determine the luminous intensity of the standard lamp. Equation (2) is the model to transfer luminous intensity from the standard lamp to the transfer lamp. The meanings of each variable are listed below.

I_1 : Luminous intensity of a standard lamp.

K_m : Maximum luminous efficiency constant. No uncertainty.

d_1 : Distance between the standard lamp and the standard photometer. Constant. No uncertainty.

Δd_1 : Deviation of distance setting.

A : Aperture area of the standard photometer.

V_0 : Voltage measured by the multimeter. Uncertainty negligible.

G : Conversion ratio of the current-voltage converter. Uncertainty negligible.

$\Phi_{e,\lambda}(\lambda)$: Relative spectral distribution of the standard lamp. Uncertainty to luminous intensity negligible.

$V(\lambda)$: Luminous efficiency function. No uncertainty.

$s_e(\lambda)$: Spectral responsivity of the standard photometer. Uncertainty of this factor consists of two parts in the budget. One is "Spectral responsivity of the silicon photodiode measured with the cryogenic radiometer", and another is " Illuminance responsivity of the standard photometer with respect to the spectral responsivity of the silicon photodiode".

c_t : Deviation of the standard photometer responsivity by the room temperature.

c_1 : Deviation of the luminous intensity measurement for the standard lamp set on and removed from the lamp mount in many times. Accumulated data.

I_2 : Luminous intensity of the transfer lamp.

k_c : Colour correction factor between the standard lamp and the transfer lamp. Uncertainty negligible.

V_2 : Voltage output measured for the transfer lamp.

V_1 : Voltage output measured for the standard lamp.

d_2 : Distance between the lamp and the comparison photometer.

Δd_2 : Deviation of distance setting.

c_i : Effect of the lamp current uncertainty.

c_a : Deviation of luminous intensity through the period of recalibraion-limit burning time. We take this effect into the uncertainty without correction. So it is listed in "Random effects" because we cannot predict what value a lamp will take at each burning.

c_2 : Deviation of the luminous intensity measurement for the transfer lamp set on and removed from the lamp mount in many times. Accumulated data.

c_3 : Fluctuation of lamp signal.

The variables correspond to the uncertainty budget as follows.

	Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
	Systematic effects:		
	Calibration of working standards		
$s_e(\lambda)$	- Spectral responsivity of the silicon photodiode measured with the cryogenic radiometer	B	0.05
$s_e(\lambda)$	- Illuminance responsivity of the standard photometer with respect to the spectral responsivity of the silicon photodiode	B	0.20
Δd_1	- Measurement of the distance between the primary standard lamp and the transfer detector	B	0.05
c_t	- Responsivity change of the transfer detector by room temperature fluctuation	B	0.10
c_1	- Setting of the luminous intensity primary standard lamp	B	0.10
A	- Aperture area	B	0.015
	Electrical		
	- standard resistor		negligible
c_i	-digital multimeter	B	0.01
	Photometer		
	- spectral mismatch		negligible
	- linearity		negligible
Δd_2	- distance	B	0.02
	Environment		
	- stray light		negligible
	- temperature / humidity ?		included in (*)
	RMS total systematic effects:		0.256

	Random effects:		
	Lamp parameters:		
c_a	- lamp ageing	B	0.11
c_2	- lamp alignment (*)	B	0.06
	- lamp reproducibility		included in (*)
c_3	- lamp output fluctuations	B	0.02
	Electrical parameters:		
	- power supply fluctuations		included in (*)
	Photometer noise		included in (*)
	(Measurement Set standard deviation of mean)		
	RMS total random effects:		0.127
	RMS total standard uncertainty:		0.29

The effect of baffles is regarded as negligibly small. We expect that that effect can be as small as 0.007 %, which is negligible in the NMIJ's uncertainty budget.

Appendix A.6 Measurement Results

Lamp Number: 37

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Feb. 2nd, 2014/11:02am	5.7563 A	29.0692 V	242.14 cd	0.127	0.256
2	2	Feb. 8th, 2014/9:57am	5.7563 A	29.0689 V	242.15 cd	0.127	0.256

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Mar. 21st, 2015/11:31am	5.7563 A	29.064 V	242.20 cd	0.127	0.256
2	2	Mar. 27nd, 2015/9:42am	5.7563 A	29.064 V	242.11 cd	0.127	0.256

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.6 Measurement Results

Lamp Number: 40

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Feb. 2nd, 2014/11:02am	5.7943 A	29.5505 V	250.55 cd	0.127	0.256
2	2	Feb. 8th, 2014/9:57am	5.7943 A	29.5493 V	250.46 cd	0.127	0.256

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Mar. 21st, 2015/11:31am	5.7943 A	29.543 V	250.34 cd	0.127	0.256
2	2	Mar. 27nd, 2015/9:42am	5.7943 A	29.544 V	250.23 cd	0.127	0.256

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.6 Measurement Results

Lamp Number: 51

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Feb. 2nd, 2014/11:02am	5.7362 A	29.2646 V	240.91 cd	0.127	0.256
2	2	Feb. 8th, 2014/9:57am	5.7362 A	29.2641 V	240.79 cd	0.127	0.256

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Mar. 21st, 2015/11:31am	5.7362 A	29.261 V	240.54 cd	0.127	0.256
2	2	Mar. 27nd, 2015/9:42am	5.7362 A	29.262 V	240.59 cd	0.127	0.256

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.6 Measurement Results

Lamp Number: 52

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Feb. 2nd, 2014/11:02am	5.7646 A	29.1676 V	241.51 cd	0.127	0.256
2	2	Feb. 8th, 2014/9:57am	5.7646 A	29.1673 V	241.49 cd	0.127	0.256

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Mar. 21st, 2015/11:31am	5.7646 A	29.160 V	241.48 cd	0.127	0.256
2	2	Mar. 27nd, 2015/9:42am	5.7646 A	29.159 V	241.50 cd	0.127	0.256

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.6 Measurement Results

Lamp Number: 58

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Feb. 2nd, 2014/11:02am	5.6101 A	29.9689 V	244.27 cd	0.127	0.256
2	2	Feb. 8th, 2014/9:57am	5.6101 A	29.9704 V	244.29 cd	0.127	0.256

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Mar. 21st, 2015/11:31am	5.6101 A	29.965 V	244.50 cd	0.127	0.256
2	2	Mar. 27nd, 2015/9:42am	5.6101 A	29.964 V	244.51 cd	0.127	0.256

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Aug. 7, 2015

Signature: 木下健一

Appendix A.6 Measurement Results

Lamp Number: 69

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Feb. 2nd, 2014/11:02am	5.6198 A	29.9204 V	243.26 cd	0.127	0.256
2	2	Feb. 8th, 2014/9:57am	5.6198 A	29.9225 V	243.09 cd	0.127	0.256

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	2	Mar. 21st, 2015/11:31am	5.6198 A	29.915 V	244.14 cd	0.127	0.256
2	2	Mar. 27nd, 2015/9:42am	5.6198 A	29.915 V	244.74 cd	0.127	0.256

Participant: Kenichi Kinoshita

NMI: National Metrology Institute of Japan

Date: Jul. 1, 2016

Signature: 木下健一

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

IO-CSIC Report

CCPR Key Comparison CCPR-K .201
Luminous Intensity

MEASUREMENT REPORT. ROUND 1

INSTITUTO DE PTICA - CSIC
MADRID-SPAIN

1.- Introduction

This report describes the procedure followed at IO-CSIC (covering first round of measurements) to determine the luminous intensity of six lamps: four OSRAM Wi 41/G identified as: Wi95A,Wi95B,Wi95C and Wi95D; and two NPL/GEC lamps (now called NPL/Polaron Heavy Current LIS incandescent lamps) identified as: A-454 and A-456.

2.- Measurement specifications

NPL/GEC lamps (now called NPL/Polaron Heavy Current LIS). 2 lamps

- Colour temperature: 2840 K ± 20 K (individual values are reported below)
- Electrical supply: Direct current, negative polarity at the central contact of the lamp base; power input specified by the current through the lamp.
- Orientation: lamp base down with the vertical window (fitted with the mask) facing the detector.
- Positioning: The rear surface of the front window is perpendicular to the optical axis, defined by the centre of the detector and the centre of the filament.
- Lamp-detector distance: 3,6 m. From the detector to the center of the filament
- The detector accepts only light passing from the black mask placed over the lamp (each lamp possess its own mask identified with the same number as the lamp)
- Warm-up time: 15 min

OSRAM lamps Wi41/G (4 lamps)

- Colour temperature: 2860 K ± 20 K (individual values are reported below)
- Electrical supply: Direct current, negative polarity at the central contact of the lamp base (E27); power input specified by the current through the lamp.
- Orientation: lamp base down, blackened part of the bulb facing the detector.
- Positioning: Plane of the filament perpendicular to the (horizontal) optical axis defined by the centre of the detector and the centre of the filament (Center Filament Support #1).
- Lamp-detector distance: 3,6 m. From the detector to the plane of the lamp filament.
- The detector accepts only the light passing through the rectangular opening in the black mask on the face of the lamp.
- Warm-up time: 15 min

.- Calibration method and Procedure

The lamps have been calibrated in an optical bench, measuring the illuminance with a V(λ) corrected detector. Two standard photometers have been used as reference, which were calibrated for absolute responsivity against our cryogenic radiometer; and for relative responsivity against the IO-CSIC spectral responsivity scale.

Two temperature-controlled, full-filtered V(λ)-corrected photometers, with aperture mode input, have been used as standards to measure illuminance at the reference plane. The IO-CSIC photometers have an input aperture diameter of approximately 9 mm.

Full description of the method used for the realization of the candela is reported in "*Realization of the candela from a partial filtering V(λ) detector traceable to a cryogenic radiometer*" by J. Campos, A. Corróns, A. Pons and P. Corredera. Metrologia. 1995, **2** and in "*Luminous intensity standard based on a cryogenic radiometer*" CIE 119-1995-23rd Session. New Delhi. Volume 1, 102-105

.- Experimental set-up

A laser beam has been used to visualize the optical axis in order to simplify the positioning and orientation of lamps and detector. A second laser beam, intercepting the first one at an angle of 45º approximately, has been used to define the reference plane for the measurement of illuminance, which is normal to the optical axis at the point where both laser beams crossed. Photometers were placed at the reference plane at normal incidence by using high precision positioning equipment. Lamp reference plane, as fixed in the measurement specifications, has been defined with a third laser beam. Figure 1

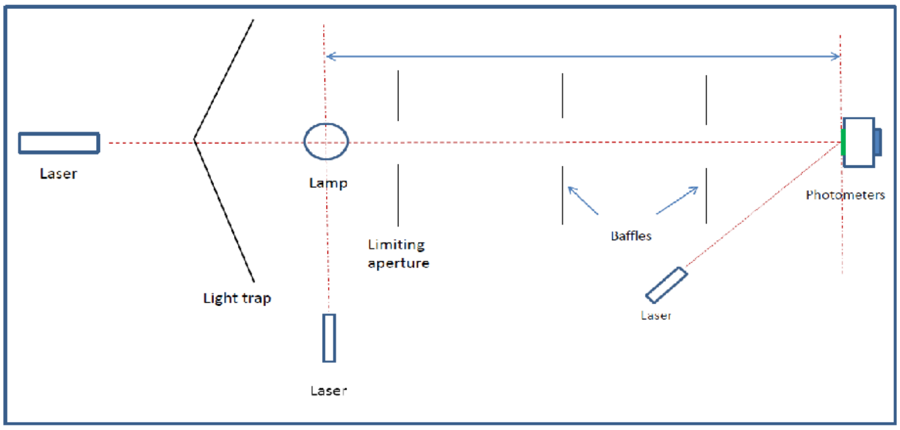


Figure 1.- Schematic of IO-CSIC Measurement Configuration

The lamps have been aligned with a cold (room temperature) filament. Next table shows individual values for electrical supply of each lamp and the measured Colour Temperature.

Lamp	Current Intensity/A	Lamp voltage/V	Colour Temperature/ K
A-	25.500	12,25	2844
A- 6	25.500	12,56	2840
i a	5.836	30,81	2869
i b	5.836	31,08	2868
i c	5.832	30,79	2862
i d	5.836	30,59	2868

Record of lamps operating time is shown in appendix A.4

.- Measurement Results

Appendix A. 6 shows the results obtained.

6.- UNCERTAINTY

Actual model of evaluation used is as expressed in equation (1)

$$I = \frac{c_v V}{S_v}\left(\frac{T_R}{T_A}\right)^m \left(\frac{c_j V_j}{J_R R_j}\right)^{m.m_T - m_I} .\left(d + \Delta d_p + \Delta d_L\right)^2 .\left(1 - c_{stray} - \varepsilon + h\varphi + f\upsilon\right) \qquad (1)$$

Quantities:

- I output quantity. Luminous Intensity
- c_v calibration factor of picoammeter. Certified value
- V mean value, averaged from the number of readings, of the photocurrent
- S_v luminous responsivity of photometer. Certified value
- T_R measured colour temperature of the lamp. Certified value
- T_A constant nominal value of colour temperature = 2856 K no uncertainty
- c_j calibration factor of the DVM to control voltage across shunt resistance
- V_j mean value voltage (lamp current), averaged from 10 readings
- J_R constant lamp current, no uncertainty
- R_j shunt resitance. Certified value
- m mismatch index, determined previously
- m_I exponent for changes of lamp current affecting luminous intensity
- m_T exponent for changes of lamp current affecting CCT
- d distance lamp-photometer
- Δd_p alignment of photometer head for distance
- Δd_L alignment of filament for distance
- c_{stray} relative correction for straylight, estimated previously
- ε angular misalignment of photometer
- $h\varphi$ angular (horizontal) misalignment of lamp
- $f\nu$ angular (vertical) misalignment of lamp

Effects of resolution of the DVM or picoammeter are negligible. Uncertainty contribution of every component is stated at appendix A.5

Appendix A.4 Record of lamp operating time

Lamp number: i A

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
16/01/2014	11 h 45 min	Measure	12 h 20 min	0,58	5,836	30,81	A.P.
16/01/2014	16h 20 min	Measure	17 h 05 min	0,75	5,836	30,80	A.P.
17/01/2014	9 h 15 min	Measure	10 h 05 min	0,83	5,836	30,81	A.P.
06/02/2014	10h 20min	Spectral distribution measurement (CCT determination)	11h 05 min	0,75	5,836	30,81	A.P.

Lamp number: i B

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
16/01/2014	9 h	Measure	9 h 35 min	0,58	5,836	31,08	A.P.
17/01/2014	11 h 20 min	Measure	11h 50 min	0,50	5,836	31,08	A.P.
18/01/2014	13 h 30 m	Measure	14 h	0,50	5,836	31,09	A.P.
06/02/2014	11h 20min	Spectral distribution measurement (CCT determination)	12h	0,67	5,836	31,08	A.P.

Appendix A.4 Record of lamp operating time

Lamp number: i C

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
16/01/2014	9 h 50 min	Measure	10 h 25 min	0,58	5,832	30,79	A.P.
17/01/2014	12 h 05 min	Measure	12 h 40 min	0,58	5,832	30,79	A.P.
17/01/2014	14 h 15 min	Measure	14 h 45 min	0,50	5,832	30,79	A.P.
06/02/2014	12 h 30 min	Spectral distribution measurement (CCT determination)	12 h 55 min	0,42	5,832	30,79	A.P.

Lamp number: i D

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
16/01/2014	15 h 30 min	Measure	16 h 10 min	0,67	5,836	30,59	A.P.
17/01/2014	10 h 20 min	Measure	10h 55 min	0,58	5,836	30,59	A.P.
17/01/2014	12 h 45 min	Measure	13 h 15 min	0,50	5,836	30,58	A.P.
06/02/2014	13 h 05 min	Spectral distribution measurement (CCT determination)	13 h 30 min	0,42	5,836	30,58	A.P.

Appendix A.4 Record of lamp operating time

Lamp number: A

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
21/01/2014	12 h 40 min	Measure	13 h 12 min	0,53	25,500	12,24	A.P.
22/01/2014	9 h 50 min	Measure	10h 30 min	0,67	25,500	12,24	A.P.
22/01/2014	16 h 05 min	Measure	16 h 40 min	0,58	25,500	12,26	A.P.
06/02/2014	17 h 20 min	Spectral distribution measurement (CCT deter-mination)	17 h 50 min	0,33	25,500	12,25	A.P.

Lamp number: A 6

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
21/01/2014	10 h 40 min	Measure	11 h 20 min	0,67	25,500	12,54	A.P.
21/01/2014	16 h 25 min	Measure	17 h 05 min	0,62	25,500	12,56	A.P.
22/01/2014	12 h 25 min	Measure	13 h 05 min	0,67	25,500	12,56	A.P.
06/02/2014	15 h 55 min	Spectral distribution measurement (CCT deter-mination)	16 h 20 min	0,42	25,500	12,56	A.P.

Appendix A.5 Sample Measurement Uncertainty Budget

Measurement parameter	Symbol	Uncertainty type (A or B)	Standard Uncertainty in luminous intensity (%)
Calibration factor of picoammeter	c_v	B	0,01
Mean value of the photocurrent	V	A	0,05
Luminous responsivity of photometer	S_v	B	0,30
Colour temperature	T_R	B	0,004
Calibration factor of multimeter used to	c_j	B	0,05
Mean value voltage (lamp current)	V_j	A	<0,0001
Shunt resistance	R_j	B	0,0007
Mismatch index	m	B	0,0002
Exponent for changes of lamp current affecting distribution temperature	m_T	B	0,0002
Exponent for changes of lamp current affecting luminous intensity	m_I	B	0,01
Distance	d	B	0,008
Locus photometer	Δd_p	B	0,01
Locus lamp	Δd_L	B	0,02
Correction for straylight	c_{stray}	B	0,02
Angle photometer	ε	B	0,002
Angle lamp	$h\varphi$	B	0,001
Angle lamp vertical	$f\nu$	B	0,02

Appendix A.6 Measurement Results

Lamp Number: i A

Measurement Round 1:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainy in Luminous Intensity (%)	
						Rando m	Systematic
1	10	16/01/2014	5,836	30,81	278,5	0,01	0,31
2	10	16/01/2014	5,836	30,80	278,5	0,03	0,31
3	10	17/01/2014	5,836	30,81	278,3	0,01	0,31

Lamp Number: i B

Measurement Round 1:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainy in Luminous Intensity (%)	
						Random	Systematic
1	10	16/01/2014	5,836	31,08	285,2	0,01	0,31
2	10	17/01/2014	5,836	31,08	285,8	0,005	0,31
3	10	18/01/2014	5,836	31,09	284,7	0,01	0,31

Lamp Number: i C

Measurement Round 1:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainy in Luminous Intensity (%)	
						Random	Systematic
1	10	16/01/2014	5,832	30,79	286,3	0,006	0,31
2	10	17/01/2014	5,832	30,79	286,8	0,003	0,31
3	10	17/01/2014	5,832	30,79	285,8	0,03	0,31

Appendix A.6 Measurement Results

Lamp Number: i D

Measurement Round 1:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	10	16/01/2014	5,836	30,59	271,8	0,006	0,31
2	10	17/01/2014	5,836	30,59	271,6	0,006	0,31
3	10	17/01/2014	5,836	30,58	272,1	0,01	0,31

Lamp Number: A

Measurement Round 1:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	10	21/01/2014	25,5	12,24	432,6	0,02	0,31
2	10	22/01/2014	25,5	12,24	433,5	0,02	0,31
3	10	22/01/2014	25,5	12,26	433,7	0,03	0,31

Lamp Number: A 6

Measurement Round 1:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	10	21/01/2014	25,5	12,54	438,6	0,05	0,31
2	10	21/01/2014	25,5	12,56	439,6	0,05	0,31
3	10	22/01/2014	25,5	12,56	439,4	0,03	0,31

RE: K3PL011: Replies to CCPR-K3.2014 Pre-Draft-A Process 2: Review of Uncertainty Budgets
2016-May-03

Dear Arnold,

Enclosed please find a the Anex 5 with an extra column with the classification of uncertainty components,

Regards,

Alicia Pons
Instituto de Optica-CSIC
Serrano 144, 28006 Madrid
Tf. 91 5618806; Fax. 91 5642122
e-mail: alicia.pons@csic.es

Appendix A.5 Sample Measurement Uncertainty Budget

Measurement parameter	Symbol	Uncertainty type (A or B)	Standard Uncertainty in luminous intensity (%)	Uncertainty type (random or systematic)
Calibration factor of picoammeter	c_v	B	0,01	systematic
Mean value of the photocurrent	V	A	0,05	random
Luminous responsivity of photometer	S_v	B	0,30	systematic
Colour temperature	T_R	B	0,004	systematic
Calibration factor of multimeter used to	c_j	B	0,05	systematic
Mean value voltage (lamp current)	V_j	A	<0,0001	random
Shunt resistance	R_j	B	0,0007	systematic
Mismatch index	m	B	0,0002	systematic
Exponent for changes of lamp current affecting distribution temperature	m_T	B	0,0002	systematic
Exponent for changes of lamp current affecting luminous intensity	m_I	B	0,01	systematic
Distance	d	B	0,008	systematic
Locus photometer	Δd_p	B	0,01	random
Locus lamp	Δd_L	B	0,02	random
Correction for straylight	c_{stray}	B	0,02	systematic
Angle photometer	ε	B	0,002	systematic
Angle lamp	$h\varphi$	B	0,001	systematic
Angle lamp vertical	$f\nu$	B	0,02	systematic

CCPR Key Comparison CCPR-K .201
Luminous Intensity

MEASUREMENT REPORT. ROUND 2

INSTITUTO DE PTICA - CSIC
MADRID-SPAIN

1.- Introduction

This report describes the values obtained in the calibration, in second round, of five lamps: four OSRAM Wi 41/G identified as: Wi95A,Wi95B,Wi95C and Wi95D; and one NPL/GEC lamps (now called NPL/Polaron Heavy Current LIS incandescent lamps) identified as: A-454. Polaron-type lamp identified as A-456 failed during the measurement at pilot laboratory.

Items related to measurement specifications, calibration method and procedure, experimental set-up and uncertainty budget are not included as they are the same as those described in the report corresponding to initial measurements.

2.- Lamp electrical values

Lamp	Current Intensity/A	Lamp voltage/V
A-	25.501	12,27
i a	5.836	30,93
i b	5.837	31,13
i c	5.832	30,86
i d	5.836	30,64

Shown values of current and voltage are effective values of electrical supply used in our laboratory, during the second round. They are mean values of the three sets of measurements made. The lamp current is measured as voltage across a shunt resistance.

Laboratory conditions

For the second round the measurements were performed during July 2015. Laboratory temperature was always between 24 ºC to 25 ºC. Humidity was in the range 30%-40%.

Record of lamp operating time

Lamp number: i A

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
13/07/2015	09 h 44 min	Measure	10 h 19 min	0,58	5,836	30,97	A.P.
17/07/2015	9h 50 min	Measure	10 h 30 min	0,67	5,836	30,95	A.P.
17/07/2015	14 h 05 min	Measure	14 h 40 min	0,58	5,836	30,87	A.P.

Lamp number: i B

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
13/07/2015	13 h 52 min	Measure	14 h 33 min	0,68	5,837	31,13	A.P.
15/07/2015	10 h 05 min	Measure	10h 40 min	0,58	5,836	31,12	A.P.
15/07/2015	13 h 36 m	Measure	14 h 15 min	0,68	5,837	31,13	A.P.

Lamp number: i C

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
14/07/2015	13 h 40 min	Measure	14 h 20 min	0,68	5,832	30,86	A.P.
16/07/2015	10 h 24 min	Measure	11 h 00 min	0,60	5,832	30,84	A.P.
16/07/2015	13 h 37 min	Measure	14 h 15 min	0,63	5,832	30,88	A.P.

Lamp number: i D

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
13/07/2015	11 h 50 min	Measure	12h 32 min	0,70	5,836	30,66	A.P.
15/07/2015	12 h 00 min	Measure	12h 42 min	0,70	5,836	30,62	A.P.
17/07/2015	11 h 58 min	Measure	12 h 30 min	0,53	5,836	30,62	A.P.

Lamp number: A

Date	Lamp ON time	Activity	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
20/07/2015	12 h 35 min	Measure	13 h 15 min	0,67	25,499	12,27	A.P.
21/07/2015	9 h 58 min	Measure	10h 35 min	0,62	25,503	12,26	A.P.
21/07/2015	12 h 44min	Measure	13 h 16 min	0,53	25,500	12,27	A.P.

4.- Measurement Results

Lamp Number: i A

Measurement Round 2:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainy in Luminous Intensity (%)	
						Rando m	Systematic
1	10	13/07/2015	5,836	30,97	278,5	0,01	0,31
2	10	17/07/2015	5,836	30,95	277,9	0,01	0,31
3	10	17/07/2015	5,836	30,87	277,9	0,03	0,31

Lamp Number: i B

Measurement Round 2:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainy in Luminous Intensity (%)	
						Random	Systematic
1	10	13/07/2015	5,837	31,13	284,5	0,02	0,31
2	10	15/07/2015	5,836	31,12	284,3	0,01	0,31
3	10	15/07/2015	5,837	31,13	284,3	0,01	0,31

Lamp Number: i C

Measurement Round 2:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	10	14/07/2015	5,832	30,86	286,4	0,01	0,31
2	10	16/07/2015	5,832	30,84	286,2	0,01	0,31
3	10	16/07/2015	5,832	30,88	285,7	0,03	0,31

Lamp Number: i D

Measurement Round 2:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	10	13/07/2015	5,836	30,66	270,9	0,006	0,31
2	10	15/07/2015	5,836	30,62	270,4	0,006	0,31
3	10	17/07/2015	5,836	30,62	270,9	0,01	0,31

Lamp Number: A

Measurement Round 2:

Measurement Set Number	Number of measurement per set	Date/time	Lamp current	Lamp voltage	Luminous Intensity	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
1	10	20/07/2015	25,499	12,27	436,2	0,02	0,31
2	10	21/07/2015	25,503	12,26	435,9	0,02	0,31
3	10	21/07/2015	25,500	12,27	436,3	0,03	0,31

2016-September-09

Dear Arnold,

Thank you for your work.

I have been analyzing the relative data of IO-CSIC and I have noticed some problems with data of Round #2 of our lamp identified as A-454.

After a detailed revision of the measurements and the calculus, I have noticed that there was an error in the data sent to you corresponding to round #2 of A-454 lamp. The problem was that in the measurements of this lamp we used a different standard resistor with a different value. At the time we calculate the luminous intensity I made a mistake.

Enclosed please find the corrected values (marked in red) for this lamp.

Lamp Number: A454

Measurement Round #2: (revised 2016-September-09)

Measurement Set Number	**Number of measurement per set**	**Date/time**	**Lamp current**	**Lamp voltage**	**Luminous Intensity**	**Standard Uncertainy in Luminous Intensity (%)**	
						Random	**Systematic**
1	10	20/07/2015	25,499	12,27	**434,8**	0,02	0,31
2	10	21/07/2015	25,503	12,26	**434,4**	0,02	0,31
3	10	21/07/2015	25,500	12,27	**434,8**	0,03	0,31

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>LNE-CNAM Report</u>

LNE-CNAM — Appendix A3

Description of measuring technique (please include a diagram):

The measurements are carried out on a photometric bench the length of which is 4 meters. Four square baffles, with external side of 400 mm and internal circular hole of 150 mm are placed between the light source and the photometer to reduce straight light. A fifth one, with a hole of 50 mm is put just after the lamp. The photometer is aligned orthogonal to the axis of the bench with a 6 degrees of freedom holder. The lampholder is set on a mechanical holder with 6 degrees of freedom too. Two sighting glasses are used for positioning the lamp on the photometric bench. One is aligned on the optical axis of the bench and is used to adjust the centre of the filament of the lamp on the bench axis. The second is perpendicular to the optical axis of the photometric bench and is used to put the filament of the lamp perpendicular to the axis of the bench and shows the origin for the distance measurement. The distance for the measurement was 2.72890(10) m (round1) and 2.73180(10) m (round2). It is read on a calibrated ruler with a resolution of 0.02 mm. The DC current in the lamps is adjusted and controlled thanks to a standard resistor and a high precision voltmeter. It is provided by a power supply with a relative stability on one hour better than 10^{-5}.

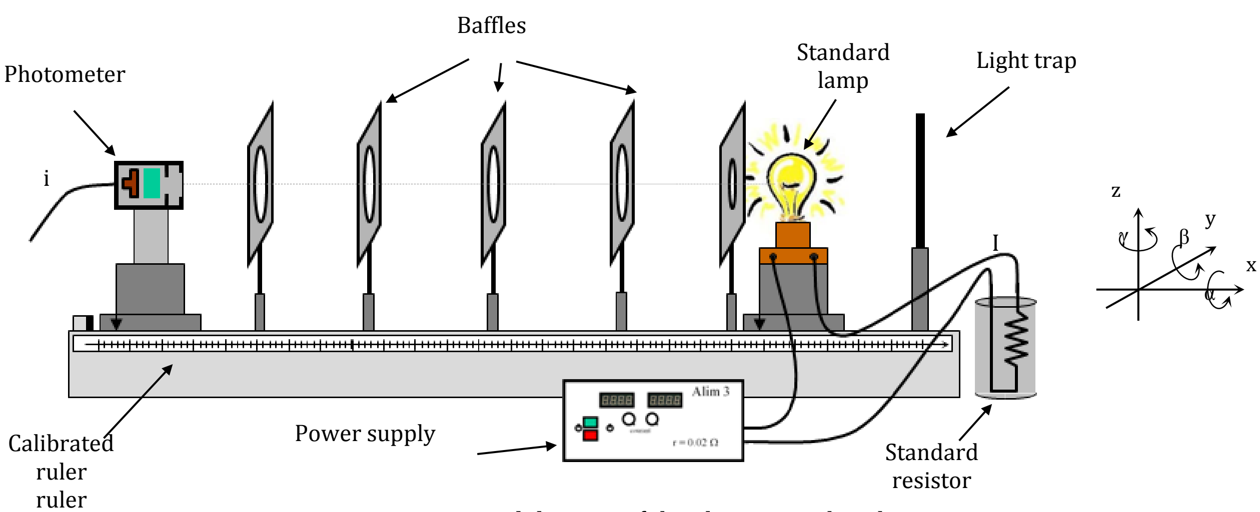


Figure1: general diagram of the photometric bench

The luminous intensity is derived from the illuminance measured by a set of three primary spectrophotometers of the laboratory according to the following procedure.

Measurement procedure.

After alignment, the lamp is switched on with a slow current ramp. We respect a warmed up of 15 mn. For each photometer, the following measurement sequence is performed:

$$\langle S_1\rangle \langle B_1\rangle \langle S_2\rangle \langle B_2\rangle \langle S_3\rangle$$

Were $\langle S_i\rangle$ is the photocurrent when looking at the lamp (30 readings).
$\langle B_j\rangle$ is the photocurrent when the lamp is hidden (30 readings).

The symmetry of the sequence allows compensating a drift of the lamp radiation.
The measurement results are

$$y_{ph} = \frac{(S_1 + S_2 + S_3)}{3};\ y_0 = \frac{(B_1 + B_2)}{3}$$

The sequence is repeated for the 3 photometers.
For each photometer, the luminous intensity of the lamp is calculated according to the measurement model described below. The result of the measurement is the average on the 3 photometers. Each lamp has been measured 2 times on each round.

Measurement model:
The measurement model is given by:

$$I_{ph}(T) = \frac{y_{ph} \cdot d^2}{S_{ph}(T)} \cdot cor$$

$$cor = \left(1 + \frac{2}{d}\left(d_L - d_{ph}\right) + \varepsilon_{ph} + \varepsilon_L - \frac{y_0}{y_{ph}} - 6.22 \cdot \Delta J - \gamma \cdot \Delta t\right)$$

Were
- I_{ph} (T) , luminous intensity when the lamp is operated perfectly
- T , colour temperature of the lamp
- d , distance between the lamp filament and the photometer limiting aperture.
- $S_{ph}(T)$, absolute sensitivity of the photometer at the colour temperature T.
- d_L , misplacement of the lamp.
- d_{ph} , misplacement of the photometer.
- y_{ph} , photocurrent corrected for straylight and offset y_0
- cor , correction factor with about unity value.
- ε_{ph} , misorientation of the photometer
- ε_L , misorientation of the lamp
- ΔJ , relative difference in the lamp current setting.
- γ , ageing coefficient of the lamp.
- Δt , burning time

Measurement uncertainty
The lamps run at a colour temperature of (2800 ± 15) K. The sensitivity of the photometers is calculated at 2800K. The slope of the spectral mismatch factor according to the CCT is low. The uncertainty component associated to the colour temperature is neglected
The other contributions to the combined uncertainty are summarised in Appendix A5.
Uncertainties on the photometer sensitivity and repeatability of the lamps are the main parts of the combined uncertainty.

Description of the primary photometers
The photometers are made with four mains parts, the trap detector, the filter holder, the filter and the aperture. The trap detector is made with three identical silicon photodiodes of 18x18mm, provided by Hamamatsu. They are oriented in order to trap the light after 5 internal reflexions and to minimize the polarization effects.

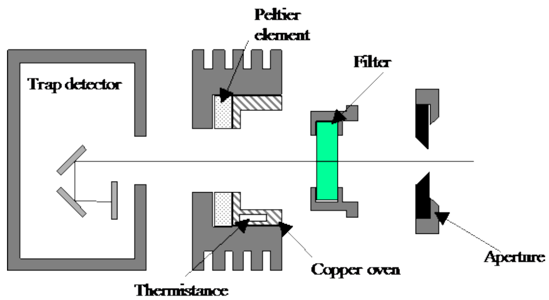


Figure 2 : General design of the photometers

The V(λ) filters are elaborated in the institute using different Schott glasses (GG10, BG39, FG13, VG4). We have 2 types of filters, made with 3 or 4 layers. As the transmittance of a filter is strongly dependent on its temperature, we designed a dedicated holder. The filter is fixed inside a copper oven and the temperature of the oven is regulated at 23°C with a Peltier element and an external controller. The temperature stability in the oven is better than 0.1 °C.
A precision aperture defines the illumination area. We have three diameters of aperture (10mm, 8mm and 6mm).
The table below details the different elements associated in the photometers.

Photometer ref	Filter	Aperture	Solid Angle
PH04A	4 layers	∅ 10 mm	10.5 µsr
PH04B	4 layers	∅ 8 mm	6.7 µsr
PH04C	3 layers	∅ 10 mm	10.5 µsr

The absolute sensibility of the trap radiometer is calibrated according to our cryogenic radiometer at 3 laser wavelengths (514.53 nm, 543.36 nm, 611.80 nm). The calibration is extended between 380 and 780 nm on our relative spectral sensitivity measurement facility.

The V(λ) is calibrated on the visible domain using our primary transmittance measurement facility. The area of the diaphragms have been calibrated on our dedicated facility.

The presentation of theses facilities and the intermediate uncertainty budget for all these calibration steps can be found in the 2 following publications

OBEIN, G., GONZALEZ-GALVAN, L., BASTIE, J., 2007, Nouvelle réalisation de la candela au LNE-INM/CNAM, *revue française de métrologie*, **12**, p19-28.

OBEIN, G., GONZALEZ-GALVAN, L., BASTIE, J., 2007, A new realization of the candela at the Lne-Inm/Cnam, *Proceedings of the 26th session of the CIE*, Vol. 1, part. 1, pp192-195.

Description of calibration laboratory conditions:
The measurements are performed at a temperature of 23 ± 1°C and a relative humidity of 50 ± 10%.

Lamps and transport issues

For this comparison, a set of 6 working luminous intensity standard lamps has been used. 3 were of type Polaron LIS (ref A430, A431, A434), 3 were of type Osram WI41/G (ref #926, #927, #936).

The 6 lamps have been sent by private transporter at NRC after the first round. The box arrived at NRC in good shape, but unfortunately, 2 polaron lamps (ref A431, A434) were broken inside. The lamps were in a wood box specially designed to protect them. They were in the institute since more than 20 years, and had already travelled many times for CCPR or EURAMET key comparisons. The shock during the transport must has been of high violence to brake the boxes and the lamps.

After discussion with the pilot lab, we took the decision to maintain the comparison on a restricted set of the 4 remaining lamps (A430, #926, #927, #936).

Unfortunately, after round2 measurements, it appears that lamp #927 shows a drift of 0.88% between Round1 and Round2. This comportment is abnormal for such a lamp. We believe that this evolution might be due to the shock during the transport. We proposed to the pilot lab to remove that lamp also.

Operating conditions of the lamps

Lamp	Current [A]	Voltage [V]	CCT [K]
926	5,690	29,01	2796
927	5,690	28,97	2795
936	5,690	29,15	2799
A430	25,000	11,95	2815

All the lamps are aligned at room temperature.

- Wi41/G lamps are aligned as in case #2 (w/2, h/2) described in the protocol section 4.4.8
- LIS Polaron lamps are aligned with retro-reflection of a laser on the front of the bulb.

The negative pole of the power supply is connected to the central electrical foot contact of the cap

LNE–CNAM — Appendix A.5 Sample Measurement Uncertainty Budget

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Electrical		
- standard resistor	B	0.02
- voltmeter	B	<0.001
Photometer		
- absolute spectral responsivity trap detector	B	0.073
- linearity	B	0.033
- filter transmission	B	0.13
- aperture surface	B	0.012
- spectral Mismatch Factor	B	0.14
- current voltage amplifier	B	0.033
- distance	B	0.004
- inter-reflection		0.05
Environment		
- stray light	B	<0.001
- temperature / humidity	B	<0.001
RMS total systematic effects:		0.22
Random effects:		
Lamp parameters:		
- lamp ageing	A	0.04
- lamp alignment	A	0.21
- lamp reproducibility	A	0.10 (typical)
Electrical parameters:		
- power supply fluctuations	A	0.01
Photometer noise	A	<0.001
RMS total random effects:		0.21
RMS total standard uncertainty:		0.32

The RMS total refers to the usual square root of the sum of the squares of all the individual uncertainty terms.

Participant: LNE-CNAM

NMI: France

Date: 27/11/2015

Signature: ………………………………

LNE-CNAM – Appendix A.6 Measurement Results

Lamp Number:

Measurement Round #1:

Lamp number	Number of measurements per set	Date/time	Lamp current [A]	Lamp voltage [V]	Luminous Intensity [cd]	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
926	2	23/03/14	5,69	29,01	234,4	0,22%	0,22%
927	2	23/03/14	5,69	28,97	238,3	0,22%	0,22%
936	2	23/03/14	5,69	29,15	241,8	0,23%	0,22%
A430	2	23/03/14	25	11,95	397,3	0,22%	0,22%

Measurement Round #2:

Lamp number	Number of measurements per set	Date/time	Lamp current [A]	Lamp voltage [V]	Luminous Intensity [cd]	Standard Uncertainty in Luminous Intensity (%)	
						Random	Systematic
926	2	21/08/15	5,69	28,97	233,8	0, 24%	0,22%
927	2	21/08/15	5,69	28,94	236,2	0,24%	0,22%
936	2	21/08/15	5,69	29,10	241,2	0,29%	0,22%
A430	2	21/08/15	25	11,96	397,4	0,24%	0,22%

The random/systematic labels in this table are those related to the measurements within the particular round of the measurements. If the systematic factors change between the measurement rounds, this information should be indicated separately.

Participant: .LNE-CNAM..................... NMI: France............................. Date: 27/11/2015

Signature: ....

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>METAS Report</u>

METAS data:

Appendix A.3 Description of the measurement facility

The items listed on this form should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated on this page. Please expand your reply document as necessary.
Description of measurement geometry (please include a diagram):

- positions of lamp, detector, bench, shielding, baffles (number, distances and sizes)

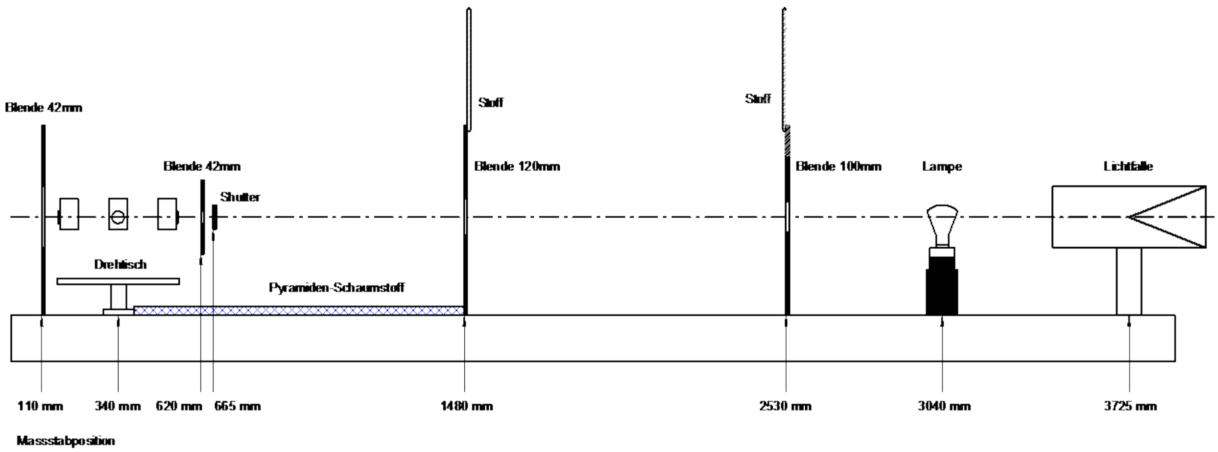


fig. 1

- alignment devices
  Laser beam, telescopes

- solid angle of luminous intensity measurements:
  1.0°

- distance of photometer from lamp
  2500 mm

- size of photometer input aperture
  8 mm (no diffusor)

- limiting aperture?
  The photometers have a sharp limiting aperture defining the reference plane

Description of measurement procedures

20 consecutive measurements of 1 s per detector 3 reference detectors

Make and type of the photometer (or equivalent).

METAS built reflective trap detector based on 3 large sized hamamatsu Si photodiode (S6337). Each photometer has a precis aperture and a *V*(λ)-matching filter . The f'_1 of the photometer being approximately 1.8. The filters are temperature stabilized

Operating conditions of the lamps:
  base down

- geometrical alignment
  The optical axis is horizontal and passes through the center of the filament.

- definitions of defined point and reference plane at the lamp
  plane of the lamp filament

- for Osram lamps with center filament supports, which center filament support type is used for the alignment (see Figure Two and Section 4.4.8.)
  CenterFilament Support #1

- alignment procedure

With the telescope in front of the lamp
Rotation about the X-axis:
the horizontal sections on each side of the filament are aligned along the Y-axis (horizontal).

The spatial position of the lamp is adjusted in the Y direction until the vertical crosshair of the telescope is equidistant from the two filament wires at the center of the filament.

The spatial position of the lamp is adjusted in the Z direction until the horizontal crosshair of the telescope passes through the defined point of the filament plane.

With the telescope in side of the lamp
Rotation about the Y-axis is adjusted until the image of the filament in the telescope is parallel to the vertical crosshair. Only the top half of the filament is visible for this alignment.

Rotation about the Z-axis is adjusted until the width (in the Y direction) of the image of the filament in the telescope is minimized. In the case of the filament with the center support, only the top half of the filament will be visible for this alignment.

The distance along the X-axis is measured to the center along the X-axis of the image of the lamp filament in the telescope.

- is the filament at room temperature or glowing for the alignment?
  room temperature

- alignment jig? If so, how is it used?
  No

- size and position of limiting aperture
  as explained above

- electrical polarity, current, voltage for each traveling standard
Positive potential on the base contact, negative potential on the thread, constant DC current

Lamp No.	Current / A	Voltage / V	CCT / K
506	5.76000	30.557 ± 0.006	2856 ± 30
684	5.68000	30.685 ± 0.006	2856 ± 30
841	5.86000	30.341 ± 0.006	2856 ± 30
1060	5.85000	30.327 ± 0.006	2856 ± 30
1063	5.90000	30.558 ± 0.006	2856 ± 30
1064	5.90000	30.682 ± 0.006	2856 ± 30

- length of warm-up time for each lamp before measurements are taken > 15 min.

- measured CCT (or Distribution Temperature or Colour Temperature, see Section 3.5).
See table

- stray-light reduction

three apertures are placed in the path between the lamp and the photometers (see also figure above): at around 100 mm from the photometer a round aperture of 42mm diameter, at 960 mm a round aperture of around 120mm and at 2000mm a round aperture of 100 mm. In addition a light trap is placed at around 725 mm after the lamp.

Description of calibration laboratory conditions: e.g. temperature, humidity etc.
T = (25.0 ± 1.0) °C and H = (40 ± 10) %

Laboratory transfer standards used:

- type of transfer standards and traceability to primary scale
the photometers are described in detail above. They are directly traceable to the METAS reference radiometers (METAS built reflective trap detector based on 3 large sized hamamatsu Si photodiode (S6337)). These radiometers are directly traceable to the METAS primary realization of optical radiation (cryo-radiometer)

Establishment or traceability route of primary scale including date of last realisation and uncertainty budget.

Participant: ……………………………..Peter Blattner
NMI: ……………………………….……METAS
Date: …………………………….………1.12.2014
Signature: ………………………………sig. P. Blattner

Appendix A.5 Sample Measurement Uncertainty Budget

Notation is based on CIE 198

$$I_{CS1} = \frac{d_{PS}^2 \left(y_{PS1} - y_{PS10}\right)}{s_{CP1}} \left(\frac{c_P}{G_{PS1}}\right) \left(\frac{T_{dC1}}{T_A}\right)^{m_{P1}} \left(\frac{c_J \cdot U_{JS1}}{J_{C1} \cdot R_J}\right)^{m_{P1} m_{TS1} - m_{IS1}} \cdot \frac{\left(1 + 2\,\Delta d_P / d_{PS} + a_P \Delta T_P + g_P(\varepsilon_P)\right)}{\left(1 + 2\,\Delta d_{S1} / d_{PS} + a_{S1} \Delta T_{S1} + k_{S1}(\varphi_{S1}) + h_{S1}(\vartheta_{S1})\right)}$$

No	Quantity	Symbol	Value	Abs. stand. uncertainty	Type	DOF	Absolute sensitivity	Absolute contribution	Relative contribution
1	distance photometer lamp / (m)	d_{PS}	2.5	0.000058	B	∞	221.1775	0.0128	0.005%
2*	mean val photo. signal / (V)	y_{PS1}	0.73384	0.00013	A	9	376.7446	0.0479	0.017%
3*	mean val photo. dark signal / (V)	y_{PS10}	-0.000438	0.000018	A	9	-376.7446	-0.0068	0.002%
4	luminous respons photometer / (nA/ lx)	s_{CP1}	16.580	0.051	B	∞	16.6746	0.8579	0.310%
5	DVM calibration factor	c_P	1	1.45E-05	B	∞	276.4719	0.0040	0.001%
6	gain setting resistance, photometer picoammeter / Kohm	G_{PS1}	1001.36	0.02	B	∞	-0.2761	-0.0044	0.002%
7*	distribution temperature of lamp / K	T_{dC1}	2855.7	11.5	B	∞	-0.0007	-0.0086	0.003%
8	nominal distribution temperature, "illuminant A" / K	T_A	2856	0	B	∞	0	0	0.000%
9	spect. mismatch factor for photometer	m_{P1}	0.0077	0.0003	B	∞	-1.09E-02	0.0000	0.000%
10	factor of the DVM used for the lamp supply	c_J	1	0.0000025	B	∞	-1'685.63	-0.0042	0.002%
11*	DVM signal of lamp supply / V	U_{JS1}	0.576091068	0.0000015	A	21	-2'925.98	-0.0044	0.002%
12	nominal current for the lamp / A	J_{C1}	5.76	0	B	∞	0	0	0.000%
13	shunt resistant used for the lamp supply / Ohm	R_J	1.000161E-01	5.00E-06	B	∞	16853.5699	0.0843	0.030%
14	relating distribution temperature with the electrical input current	m_{TS1}	0.4	0.2	B	∞	-2.67E-06	0.0000	0.000%
15	exponent for current sensitivity of intensity	m_{IS1}	6.1	2	B	∞	3.48E-04	0.0007	0.000%
16*	distance alignment of photometer head	$\Delta d_P / d_{PS}$	0	0.000046	B	∞	552.9438	0.0254	0.009%
17	relative temperature coefficient of photometer / K-1	α_P	0.0002	0.0001	B	∞	276.4719	0.0276	0.010%
18	deviation to nominal ambient temperature DUT/ K	ΔT_P	1	0.28	B	∞	0.0553	0.0155	0.006%
19*	angular misalignment of DUT photometer head	$g_P(\varepsilon_P)$	0	0.00007	B	∞	276.4719	0.0194	0.007%
20*	distance alignment of lamp filament	$\Delta d_{S1} / d_{PS}$	0	0.00023094	B	∞	-552.9438	-0.1277	0.046%
21	relative temperature coefficient of lamp / K-1	α_{S1}	0.0002	0.0001	B	∞	0.0000	0.0000	0.000%
22	deviation to nominal ambient temperature ref/ K	ΔT_{S1}	0	0.28	B	∞	-0.0553	-0.0155	0.006%
23*	angular misalignment of ref photometer head	$k_{S1}(\varphi_{S1})$	0	0.000054	B	∞	-276.4719	-0.0149	0.005%
24*	angular misalignment of ref photometer head	$h_{S1}(\vartheta_{S1})$	0	0.0002	B	∞	-276.4719	-0.0553	0.020%
	luminous intensity lamp / (cd)	s_{CP1}	276.47		DOF	1.0E+06		0.8761	0.317%

Peter Blattner, METAS, 2015-11-07

Appendix A.6 Measurement Results

METAS Peter Blattner 07.11.2015

Lamp Number	**506**
CCT	2855.74 K

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
732	10	12.02.2014	14:28	5.76	30.558	276.357	0.054	0.312
738	10	17.02.2014	14:46	5.76	30.559	276.104	0.053	0.312

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
783	10	30.04.2014	13:12	5.76	30.558	276.241	0.054	0.312
783b	10	30.04.2014	16:15	5.76	30.557	276.148	0.052	0.312

Lamp Number	**684**
CCT	2854.35 K

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
733	10	13.02.2014	12:36	5.68	30.687	278.005	0.074	0.312
737	10	14.02.2014	15:55	5.68	30.688	277.937	0.064	0.312

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
784a	10	04.05.2015	13:57	5.68	30.685	277.785	0.053	0.312
784b	10	04.05.2015	17:50	5.68	30.686	277.989	0.056	0.312

Lamp Number	**841**
CCT	2858.30 K

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
734	10	13.02.2014	14:46	5.86	30.341	280.804	0.053	0.312
736	10	14.02.2014	13:58	5.86	30.341	280.953	0.055	0.312

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
785a	10	05.05.2015	11:50	5.86	30.335	280.345	0.054	0.312
785b	10	05.05.2015	15:42	5.86	30.338	280.279	0.052	0.312

Lamp Number	**1060**
CCT	2840.96 K

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
729	10	11.02.2014	07:43	5.85	30.323	272.283	0.056	0.312
740	10	18.02.2014	08:34	5.85	30.327	272.230	0.053	0.312

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
787a	10	06.05.2015	09:17	5.85	30.340	272.931	0.055	0.312
787b	10	06.05.2015	13:21	5.85	30.337	273.036	0.052	0.312

Lamp Number	**1063**
CCT	2854.46 K

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
730	10	11.02.2014	12:15	5.90	30.555	283.875	0.053	0.312
741	10	18.02.2014	10:31	5.90	30.559	284.103	0.056	0.312

Measurement Round #2:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
825a	10	29.07.2015	13:48	5.90	30.571	284.303	0.052	0.312
825b	10	29.07.2015	16:40	5.90	30.565	284.508	0.054	0.312

Lamp Number	**1064**
CCT	2854.84 K

Measurement Round #1:

Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
731	10	11.02.2014	15:41	5.90	30.676	287.852	0.053	0.312
742	10	18.02.2014	12:14	5.90	30.682	287.963	0.052	0.312

Measurement Round #2:								
Measurement Set Number	Number of measurements per set	Date	Time	Lamp current / A	Lamp voltage / V	Luminous Intensity / cd	Standard Uncertainty in Luminous Intensity (%)	
							Random	Systematic
826a	10	30.07.2015	15:24	5.90	30.696	288.605	0.052	0.312
827b	10	30.07.2015	18:10	5.90	30.689	288.519	0.053	0.312

Blattner Peter

Digitally signed by Blattner Peter DN: cn=Blattner Peter, o=METAS, ou,
email=peter.blattner@metas.ch, c=CH
Date: 2015.11.07 22:23:01 +01'00'

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

NPL Report

National Physical Laboratory

NPL REPORT ENV (RES) 00

MEASUREMENTS OF LUMINOUS INTENSITY STANDARDS FOR CCPR KEY COMPARISON CCPR-K .201

BARRY SCOTT, TERESA OODMAN

APRIL 2016

National
Measurement
System

Measurements of Luminous Intensity Standards for CCPR Key Comparison CCPR-K3.2014

Barry Scott & Teresa Goodman
Environment Division

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by
Dr Richard Brown, Knowledge Leader

CONTENTS

1 INTRODUCTION

NPL is one of twelve laboratories that has participated in the CCPR Key Comparison CCPR K3:2014 for Luminous Intensity which commenced in 2014. This report summarises the results of the measurements performed at NPL of the selected Luminous Intensity Standard lamps.

2 SELECTION OF COMPARISON ARTEFACTS

The comparison protocol called for luminous intensity standard lamps as the comparison artefacts. The nominated lamp types were Osram Wi41/G lamps and NPL/Polaron LIS lamps. Participants were requested to submit between four and six lamps which could be of either one or both types. NPL chose to submit five lamps as travelling artefacts, three Polaron type and two Osram type, as indicated in Table 1.

Table 1 NPL Travelling Artefacts

Source Type	Identifier
NPL/Polaron	A644
NPL/Polaron	A647
NPL/Polaron	PA758
Osram Wi41/G	877
Osram Wi41/G	890

3 MEASUREMENT FACILITY

Measurements were performed at NPL on the 8 m photometric bench facility, shown schematically in Figure 1. The primary optical axis for this facility is defined by a laser aligned to run parallel to the bench and the datum position is defined by the vertical crosshair of a cathetometer which is aligned perpendicular to the optical axis. Distance is determined by a vernier length scale which has been calibrated using a laser interferometer.

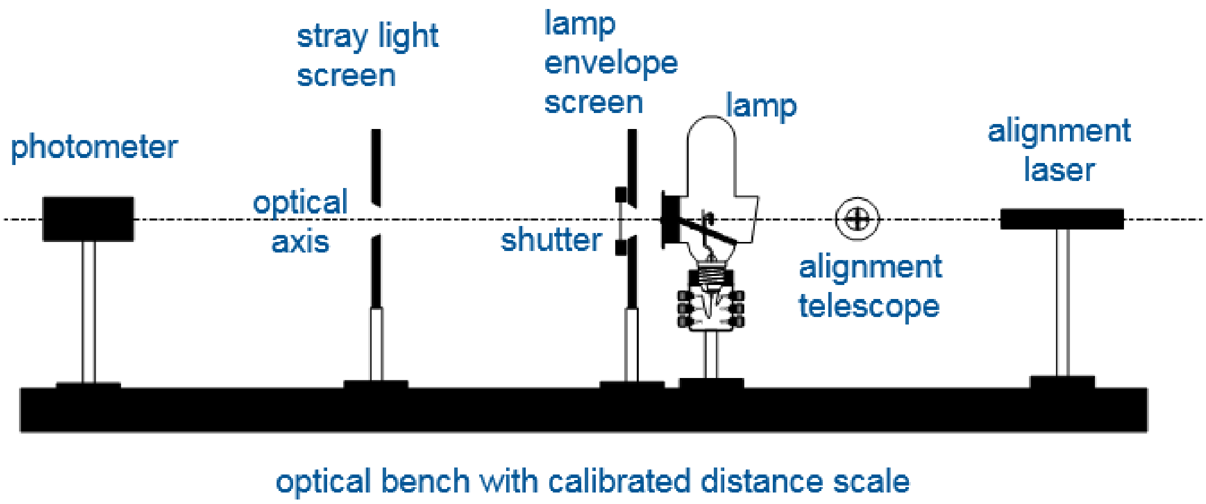


Figure 1 NPL 8 m bench facility

An NPL-designed photometer was used to transfer the calibration from the NPL primary standard luminous intensity lamps to the travelling standard lamps used for the comparison. The photometer consists of a single element silicon photodiode with a four-element glass filter, which has been individually-designed to give a close match to the $V(\lambda)$ function, and a precision aperture (10 mm in diameter) which defines the photometer reference plane for distance measurement. The photometer was aligned so that the aperture was perpendicular to, and centred on, the optical axis. The complete unit was temperature-controlled at 30.0 ºC; the spectral responsivity of the photometer has also been calibrated at this temperature.

Stray light was minimised using a series of baffles between the lamp being measured and the photometer (three baffles were used, placed approximately 200 mm, 1900 mm and 2100 mm from the limiting aperture of the photometer – exact placement of the baffles depended on a visual assessment of stray light reaching the photometer). An additional baffle was placed immediately in front of the lamp so that only light passing through the lamp mask could reach the photometer. A black cloth screen was placed between the rear of the lamp and the alignment laser to eliminate reflections from the laser aperture. The walls, floor and ceiling of the laboratory are painted black. Residual stray light was allowed for by making a 'dark' measurement with the stray light screen closest to the lamp obstructed.

Measurements were made with the lamps aligned as described in Section 3.1 below with the photometer set so that its limiting aperture was at a distance of 2.4 m from the mean plane of the lamp filament; this gave a measurement solid angle of approximately 0.12 sr. The reference standards used were of the same type as the travelling standards and were aligned in the same way and measured at the same distance. The reference standards were directly traceable to NPL's cryogenic radiometer and were established as described in [1]. The NPL luminous intensity scale has been re-established directly against the cryogenic radiometer on a regular basis since the time of the first realisation described in [1] and this has confirmed the stability of the disseminated scale over this period. The calibration of the reference lamps has also been checked at regular intervals and found to be within the limits allowed for 'lamp ageing' in the uncertainty budget.

The lamps were operated from a stabilised dc power supply with a current stability of better than 0.005 %. Current was determined by measuring the voltage drop across a calibrated precision resistor (0.1 Ω in the case of the Osram lamps, 0.01 Ω for the Polaron lamps); the resistors were used in an oil bath to minimise any temperature fluctuations during use and were calibrated at the same temperature at which they were used. Each lamp had previously been calibrated against the NPL relative spectral irradiance scale to determine the current required for a correlated colour temperature of approximately 2856 K and this was the current set for this comparison; the individual lamp currents set and the corresponding correlated colour temperatures are given in Table 2. The reference lamps were also operated at a correlated colour temperature of approximately 2856 K and the close match of the photometer spectral responsivity to the $V(\lambda)$ function meant that the spectral mismatch correction was negligibly small.

At least two independent measurements were made on each lamp, with the lamp being completely realigned for each measurement. Measurements were made over a period of several days. On each occasion of measurement the lamp was run up gradually to the required current and allowed to stabilise for at least 15 minutes before measurements commenced. The lamps were operated in a 4-pin lamp holder and the lamp voltage and current at the time of measurement were recorded, together with the photocurrent from the photometer.

Table 2 Currents and correlated colour temperatures for NPL travelling artefacts

Lamp identifier	Current (A)	Correlated colour temperature (K)
A644	25.360	2850
A647	25.310	2850
PA758	25.220	2850
877	5.818	2853
890	5.804	2853

During the course of the measurements the laboratory was maintained at a temperature of 21.0 ºC ± 2.0 ºC and a humidity of 50 % RH ± 25 % RH.

3.1 LAMP ALIGNMENT

The lamps were mounted base down and aligned with a cold filament (i.e. no current flowing).

The alignment procedure used for the Osram lamps was as follows:

1. The lamp was adjusted so that the filament was vertical when viewed along the optical axis.
2. The lamp was rotated so that the width of the image of the filament viewed through the cathetometer set perpendicular to the optical axis was minimised.
3. The tilt of the lamp was adjusted so that the image of the filament was vertical (i.e. parallel to the cathetometer vertical cross hair)
4. The lamp was adjusted in the horizontal and vertical direction so that the laser defining the optical axis passed through the centre of the filament.
5. A screen was placed immediately in front of the lamp so that only light passing through the aperture in the painted lamp mask could reach the photometer.
6. Distance was measured from the mean plane of the lamp filament as viewed using the cathetometer mounted perpendicular to the optical axis of the optical bench. The measurement distance was 2.40 m.

The alignment procedure used for the Polaron lamps was as follows:

1. The lamp was adjusted so that the envelope was vertical when viewed along the optical axis.
2. The lamp was rotated and tilted so that the flat front window was set perpendicular to the optical axis (i.e. so that the laser defining the optical axis was reflected from the rear of the front window directly back to the laser).
3. The lamp was adjusted in the horizontal and vertical direction so that the laser defining the optical axis passed through the centre of the filament.
4. A screen was placed immediately in front of the lamp so that only light passing through the aperture in the lamp mask fixed to the front window could reach the photometer.

5. Distance was measured from the mean plane of the lamp filament as viewed using the cathetometer mounted perpendicular to the optical axis of the optical bench. The measurement distance was 2.40 m.

4 RESULTS

Table 3 Measurement Round #1, March 2014

Source Identifier	Lamp Current (A)	Lamp Voltage (V)	Luminous Intensity (cd)	Number of independent measure-ments	Standard Uncertainty in Luminous Intensity (*k* = 1) Random (%)	Systematic (%)
A644	25.360	12.505	451.78	3	0.082 %	0.158 %
A647	25.310	12.510	459.43	2	0.082 %	0.158 %
PA758	25.220	12.743	460.33	3	0.082 %	0.158 %
877	5.818	30.013	276.34	2	0.082 %	0.158 %
890	5.804	29.871	273.93	3	0.082 %	0.158 %

Table 4 Measurement Round #2, September 2015

Source Identifier	Lamp Current (A)	Lamp Voltage (V)	Luminous Intensity (cd)	Number of independent measure-ments	Standard Uncertainty in Luminous Intensity (*k* = 1) Random (%)	Systematic (%)
A644	25.360	12.500	451.97	2	0.082 %	0.158 %
A647	25.310	12.533	459.63	2	0.082 %	0.158 %
PA758	25.220	12.751	460.70	2	0.082 %	0.158 %
877	5.818	30.013	275.91	3	0.082 %	0.158 %
890	5.804	29.878	273.24	2	0.082 %	0.158 %

5 UNCERTAINTY BUDGET

Table 5 Uncertainty budget (identical for both rounds of measurements and both types of lamp)

Source of uncertainty	Type A or Type B	value	Divisor	u_i
Systematic effects:				
Calibration of reference lamp intensity	B	0.200 %	2	0.100 %
Ageing of reference lamps	B	0.125 %	1.732	0.072 %
Distance setting	B	0.050 %	1.732	0.029 %
Accuracy of lamp current setting	B	0.160 %	1.732	0.092 %
Photocurrent measurement	B	0.010 %	1.732	0.006 %
Spectral mismatch	B	0.010 %	1.732	0.006 %
Stray light	B	0.020 %	1.732	0.012 %
RMS Total Systematic Effects				0.158 %
Random effects:				
Stabiliser current control	A	0.016 %	2	0.008 %
Photometer calibration factor repeatability	A	0.064 %	1	0.064 %
Test lamp repeatability	A	0.050 %	1	0.050 %
RMS Total Random Effects:				0.082 %
RMS Total Standard Uncertainty				0.178 %

The basis of these uncertainties is described in 5.1 to 5.10 below. The associated measurement equation is:

$$I_{\mathrm{v},t} = C_{\mathrm{cal}} V_t (1 + C_{\mathrm{d},t})(1 + C_{\mathrm{J},t})(1 + C_{\mathrm{p},t}) F_{\mathrm{SM},t} (1 - C_{\mathrm{stray},t})(1 + C_{\mathrm{align},t}) \quad (1)$$

where

$$C_{\mathrm{cal}} = \frac{(I_{\mathrm{v},r} + C_{\mathrm{age},r})}{V_r} \quad (2)$$

and

$I_{\mathrm{v},t}$ is the luminous intensity of test (comparison) lamp *t*

C_{cal} is the mean photometer calibration factor, calculated using Equation 2 and averaged across all the reference lamps used

$I_{\mathrm{v},r}$ is the luminous intensity of reference lamp *r*

$C_{\mathrm{age},r}$ is the change in luminous intensity of reference lamp *r* since its original calibration due to ageing

V_r is the mean reading from the photometer for reference lamp *r*

V_t is the mean reading from the photometer for test lamp *t*

$C_{\mathrm{d},t}$ is the error in luminous intensity for test lamp *t* due to error in setting the filaments of the reference and test lamps in the same vertical plane

$C_{J,t}$ is the error in luminous intensity for test lamp *t* due to error in setting the current for the test lamp to the specified value (the uncertainty due to error in setting the current for the reference lamp to the specified value is included in the uncertainty budget for the luminous intensity of the reference lamp)

$C_{\mathrm{p},t}$ is the error in luminous intensity for test lamp *t* due to differences in amplifier gain and DVM sensitivity between measurement of the photocurrent produced by the reference lamp and that produced by the test lamp

$F_{\mathrm{SM},t}$ is the spectral mismatch correction factor for test lamp *t*

$C_{\mathrm{stray},t}$ is the error in luminous intensity for test lamp *t* due to differences in stray light between the reference and test lamps

$C_{\mathrm{align},t}$ is the error in luminous intensity for test lamp *t* due to misalignment of the lamp (the uncertainty due to misalignment of the reference lamp is included in the uncertainty budget for the luminous intensity of the reference lamp)

Note all of the C terms listed above have an expected value of zero and an associated uncertainty that has been estimated as described in sections 5.1 to 5.10 below.

5.1 CALIBRATION OF REFERENCE LAMP INTENSITY

The calibration of the reference lamps, and the associated uncertainties, is detailed in [1].

5.2 AGEING OF REFERENCE LAMPS

The reference lamps are used only for checks to confirm the stability of the NPL luminous intensity scale and as standards for calibration of working standards. They have been used for a maximum of 25 hours since their initial calibration (most have been used for less than this) and their polarity is reversed on each occasion of use to minimise ageing effects. Measurements on other lamps of the same type operated at the same correlated colour temperature and under the same conditions have shown ageing rates of approximately 0.5 % per 100 hours; a conservative allowance for ageing of 0.125 % has therefore been included in the uncertainty budget to allow for ageing. Regular checks using the NPL photometer as a reference (freshly calibrated against the cryogenic radiometer) have confirmed the reference lamps have been stable to within this limit.

5.3 DISTANCE SETTING AND BENCH SCALE

The reference lamps and the travelling standards are both used at the same distance, which is also the distance at which the reference lamps were originally calibrated. Therefore the only contributions that need to be considered when assessing the uncertainty due to distance setting are the precision with which the bench scale can be read (since this limits the ability to set a reproducible distance value) and the uncertainty in defining the mean plane of the filament. The combined effect of these two contributions is estimated as 0.5 mm, which corresponds to an uncertainty in luminous intensity of 0.05 % at the measurement distance of 2.40 m.

5.4 ACCURACY OF LAMP CURRENT SETTING

The accuracy of the lamp current setting is determined by the uncertainty associated with the calibration of the standard resistor (including an allowance for possible drift in the resistance since the time of calibration) and the uncertainty associated with the calibration of the voltmeter (again including an allowance for possible drift since the time of calibration). These were estimated to give a combined uncertainty of 0.02 % in current, which corresponds to an uncertainty of 0.160 % in luminous intensity (using an 8:1 relationship between intensity and current).

5.5 PHOTOMETER PHOTOCURRENT

Since the measurement procedure used at NPL involves a direct comparison between lamps of similar types, the majority of the factors that influence the accuracy of the measurement of the photometer photocurrent (such as amplifier gain and digital voltmeter accuracy) have negligible impact on the final luminous intensity value. A small contribution (0.01 %) is included in the uncertainty budget to allow for any residual uncertainty e.g. due to the effect of ambient temperature fluctuations.

5.6 PHOTOMETER SPECTRAL MISMATCH

As indicated in Section 3, the reference and test lamps have similar correlated colour temperatures and the photometer has a good match to the $V(\lambda)$ function (f_1' better than 3.5 %). No spectral mismatch correction was therefore necessary, but a small contribution (0.01 %) was allowed for spectral mismatch in the uncertainty budget.

5.7 STRAY LIGHT

Stray light was minimised through the use of stray light screens between the lamp and the photometer. A small contribution of 0.02 % was included in the uncertainty budget to allow for any residual stray light.

5.8 STABILISER CURRENT CONTROL

The lamps were operated from a stabilised power supply, able to control current to 0.002 %. The corresponding uncertainty in lamp luminous intensity was estimated as 0.016 % (using an 8:1 relationship between intensity and current).

5.9 PHOTOMETER CALIBRATION FACTOR

The repeatability of the photometer calibration factor was determined by statistical analysis of the results using a number of the NPL reference standard lamps. The standard uncertainty was included as a Type A contribution in the uncertainty budget.

5.10 TEST LAMP REPEATABILITY

The repeatability of the measurements on the test lamps was estimated based on statistical analysis of the results of previous measurements on similar lamps, in which the lamp was realigned a number of times at various extremes of what would be regarded as an ‘acceptable’ alignment. In practice, the measurement repeatability achieved was better than this, but the worst case estimate (0.05 %) was used in the uncertainty budget.

6 REFERENCES

[1] Goodman TM and Key PJ. The NPL radiometric realisation of the candela. Metrologia 1988; 25: 20-40.

NPL response to questions relating to uncertainty budgets for CCPR-K3.2014

General comments / questions

1. The lamps used for the comparison were calibrated directly against NPL's primary reference standard luminous intensity lamps, which are of exactly the same type as the comparison lamps. Any reflections from the inside edges of baffles or shutters are therefore common to both the reference and comparison lamps and the effects cancel; no correction is necessary. Extensive investigations into stray light effects (including light scattered, reflected or diffracted by apertures and baffles) were carried out during the realisation of the luminous intensity scale and assessed to be less than 0.01 % - this is included in the uncertainty budget for NPL's realisation of the candela.

2. The alignment of the NPL photometer was not changed between the calibration using the reference lamps and the measurements of the comparison lamps; therefore it is not necessary to include an uncertainty component for misalignment of the photometer aperture.

3. NPL did not follow the model given in CIE 198:2011 since this is not how we usually structure our uncertainty budget. We did, however, provide a detailed description of each of the uncertainty contributions included in our uncertainty budget, which we believe gives the information necessary to judge the legitimacy of each of these. For completeness, our measurement equation is given below (this has also been added to our measurement report):

$$I_{\mathrm{v},t} = C_{\mathrm{cal}} V_t (1 + C_{\mathrm{d},t})(1 + C_{\mathrm{J},t})(1 + C_{\mathrm{p},t}) F_{\mathrm{SM},t} (1 - C_{\mathrm{stray},t})(1 + C_{\mathrm{align},t}) \quad (1)$$

where

$$C_{\mathrm{cal}} = \frac{(I_{\mathrm{v},r} + C_{\mathrm{age},r})}{V_r} \quad (2)$$

and

$I_{\mathrm{v},t}$ is the luminous intensity of test (comparison) lamp *t*

C_{cal} is the mean photometer calibration factor, calculated using Equation 2 and averaged across all the reference lamps used

$I_{\mathrm{v},r}$ is the luminous intensity of reference lamp *r*

$C_{\mathrm{age},r}$ is the change in luminous intensity of reference lamp *r* since its original calibration due to ageing

V_r is the mean reading from the photometer for reference lamp *r*

V_t is the mean reading from the photometer for test lamp *t*

$C_{\mathrm{d},t}$ is the error in luminous intensity for test lamp *t* due to error in setting the filaments of the reference and test lamps in the same vertical plane

$C_{\mathrm{J},t}$ is the error in luminous intensity for test lamp *t* due to error in setting the current for the test lamp to the specified value (the uncertainty due to error in setting the current for the reference lamp to the specified value is included in the uncertainty budget for the luminous intensity of the reference lamp)

$C_{\mathrm{p},t}$ is the error in luminous intensity for test lamp t due to differences in amplifier gain and DVM sensitivity between measurement of the photocurrent produced by the reference lamp and that produced by the test lamp

$F_{\mathrm{SM},t}$ is the spectral mismatch correction factor for test lamp t

$C_{\mathrm{stray},t}$ is the error in luminous intensity for test lamp t due to differences in stray light between the reference and test lamps

$C_{\mathrm{align},t}$ is the error in luminous intensity for test lamp t due to misalignment of the lamp (the uncertainty due to misalignment of the reference lamp is included in the uncertainty budget for the luminous intensity of the reference lamp)

Note all of the C terms listed above have an expected value of zero and an associated uncertainty that has been estimated as described in our measurement report.

Specific comments / questions

1. Yes, it is impossible to isolate the effect of ‘stabiliser current control’ from ‘test lamp repeatability’ so there is potentially a small element of double counting in the random effects. However since the test lamp repeatability component is intended primarily to allow for lamp alignment variations and is treated as a worst case estimate, we have chosen to ignore this small element of double counting. The effect on the final uncertainty is insignificant.

2. We do not know the actual change in luminous intensity due to ageing for each individual reference lamp used. Each reference lamp has been used for a different length of time since the original calibration and will also age at a slightly different (unknown) rate. We therefore do not correct for ageing effects. The uncertainty estimate is a conservative allowance, which is based on measurements on other lamps of the same type operated at the same correlated colour temperature and under the same conditions coupled with knowledge of the maximum length of time for which the reference lamps have been used since the original calibration.

3. We apologise for these typing mistakes, which were due to importing the table from an Excel file. We have provided a corrected version of the report to the pilot laboratory.

4. The uncertainty due to lamp alignment is included under ‘Test lamp repeatability’ as described in section 5.10 of our report.

Dear Arnold,

Many thanks for sending the NPL relative data for CCPR-K3.2014 for review. I have the following comments:

1. We had noted from our measurements that the luminous intensity values for our two Wotan lamps, 877 and 890, were significantly different for our round 1 and round 2 measurements; the differences were significantly larger than would be expected based on the random uncertainty associated with measurements of these lamps. The Polaron lamps showed much better stability during the course of the comparison, with values from the two rounds agreeing at the levels we would expect (i.e. within the random uncertainty).

2. This suggested that the luminous intensity of both Wotan lamps had changed as a result of transportation. Other possible causes of a change in output, such as ageing, appeared unlikely because of the very short burn time during the course of the comparison measurements. Furthermore, we considered it likely that the change in output would have occurred either during transportation to NRC or during return to NPL; changes during both transportations could occur, but are less probable.

3. We obviously could not tell from our measurements whether the values had changed during the first transportation, from NPL to NRC, or during the second, from NRC to NPL. Based on the evidence of the relative data, it appears that for both lamps the change is most likely to have occurred after the NRC measurements, i.e. during transport back to NPL. This is demonstrated by the small standard deviation in the candela/volt ratios using the Round 1 luminous intensity values (0.06 %, which is consistent with the random uncertainties of 0.08 %) compared with the much larger standard deviation using the round 2 values (0.14 %, which is significantly higher than the random uncertainties).

4. Based on this review, I would request that the analysis for the NPL Wotan lamps should use only the round 1 luminous intensity values. Both rounds of measurements should be used for the Polaron lamps.

Please let me know whether this is acceptable. I am happy to give further details if necessary.

Best wishes

Teresa

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>PTB Report</u>

Appendix A.3

Description of the measurement facility at PTB

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Description of measuring geometry

The measurements are carried out at the photometer bench system. The photometer bench system is composed of three different photometer benches aligned in a row. They can be used singly or together, so that measuring distances up to 40 meter become possible. The distance readings are from absolute electronic linear encoders with resolution below 0.01 mm and linear well within that range. The calibration of all geometric relations is performed by a laser-tracker. The latter is traced back to the national PTB length standard with an expanded uncertainty of 0.1 mm for distances up to 8.5 m. The following Fig. 1, 2, 3, 4 and 5 show the main components of the bench and illustrate their interactions.

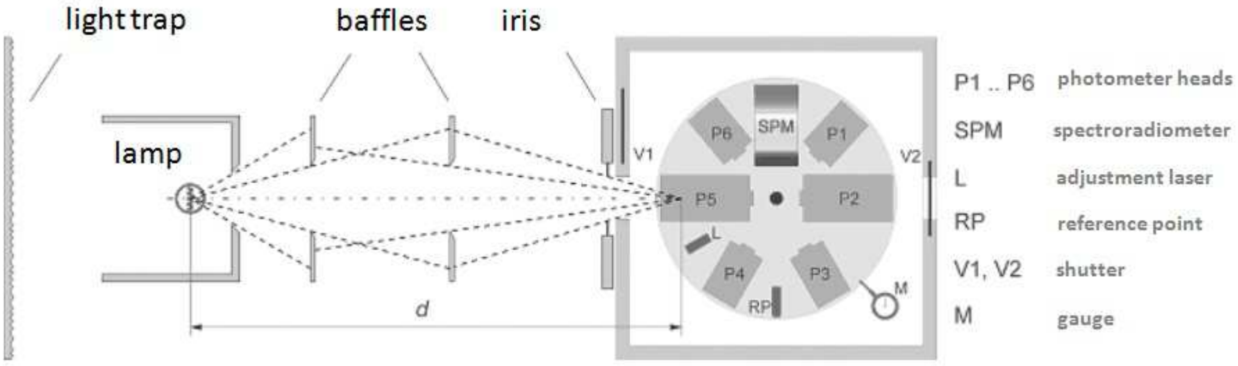


Fig. 1: Main components of the photometer bench (schematic) including light trap, baffles and the aperture plus shutter for field-of-view limitation and dark measurements, respectively.

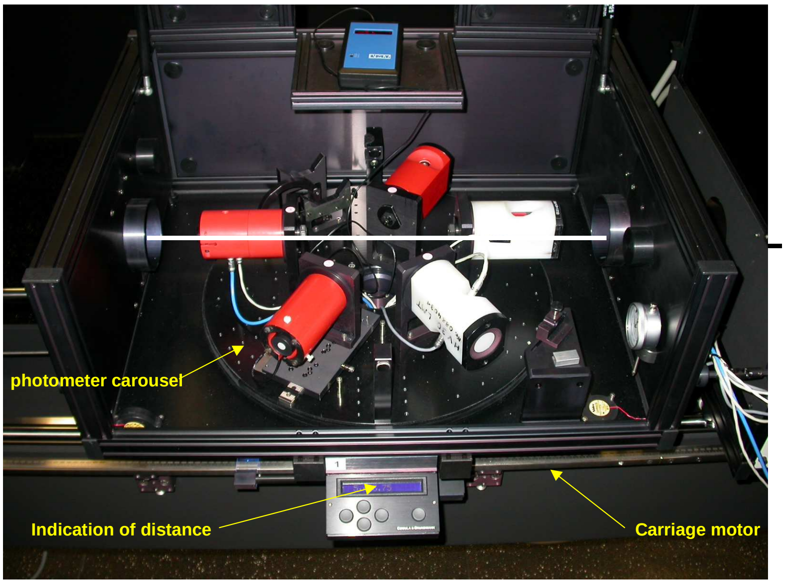


Fig. 2: Photometer carousel performing sequential measurement with up to 6 photometers / spectrometers mounted to the identical location with their limiting aperture

1

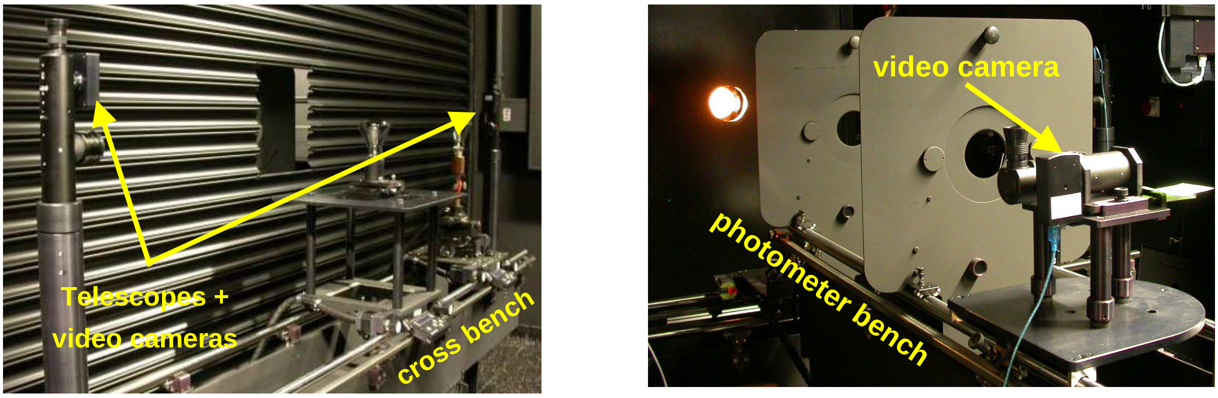


Fig. 3: Tools for the camera aided alignment are two video cameras (left) to the left and right side of the lamp and, behind the rolling gate, the third video camera (right) mounted temporarily within the photometer bench for front view.

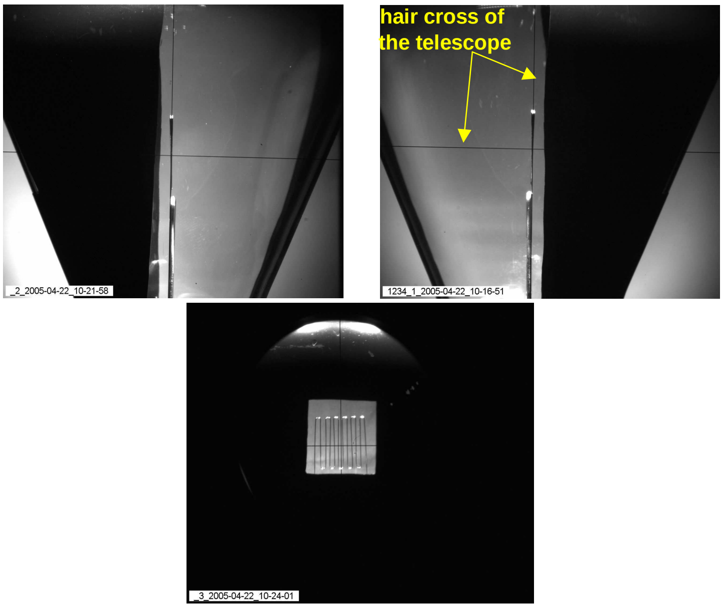


Fig 4: Images of the lamp's filament from left and right side (on top) and the front view (bottom).
Note: The light trap behind the filament is temporarily covered with a higher reflecting cloth to enlarge the contrast within the image.

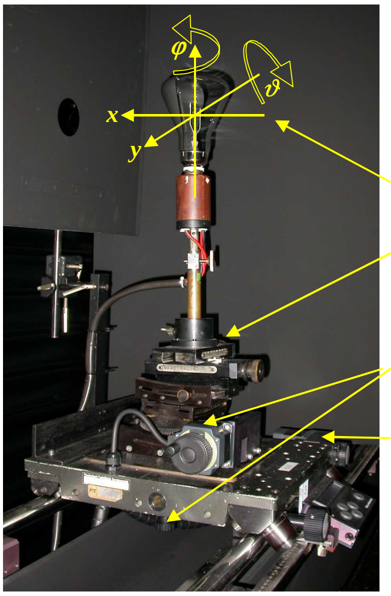


Fig.: 5: Automated lamp holder with:
Motors and lamp power supply being
- software controlled, enabling
- automated determination of related
- the sensitivity coefficients
$c(x), c(y), c(\vartheta), c(\varphi), c(i_{\text{lamp}}), c(T(i_{\text{lamp}}))$
Motor driven photometer carriage for a variation of the distance "*x*".
Lamp holder, for an independent alignment of 6 degrees of freedom
Lamp carriage with three motors for
- rotating the "aligned lamp" around the two axes "ϑ" and "φ" and for
- moving in direction "*y*".

Description of measurement procedure

At the PTB the unit of luminous intensity is the realized and maintained by a network of lamps and photometers [1]. All objects are characterized over long periods of time and well known for their relevant properties such as coefficients for ageing, geometrical misalignment, electric misadjustment, and ambient influences (temperature, humidity, air stream).
The 6 lamp transfer standards participating in this key comparison are organized as a fixed group since the last CCPR key comparison [2] which acts as a PTB- internal duplication for the lamp transfer standard group taking part in the last key comparison. Since then, they were operated for only 4 hours and were calibrated according to the value represented by PTBs network of lamps (see "Traceability chain and date of last realization"), before transport to the pilot laboratory. Hence, their values represent the valid national luminous intensity unit of PTB.

Make and type of the photometer

Two photometer heads LMT with thermostatic stabilization at 35°C are used and permanently heated.

a) Type P30, aperture with diffuser, the reference plane is outside of the opal glass of the entrance window (diameter 30 mm)
b) Type P10, aperture without diffuser, the reference plane is outside of the glass of the entrance window (diameter 10 mm)

Description of calibration laboratory conditions

- ambient temperature 23.5°C (± 0.5°C)
- relative humidity 45% (± 10%)
- clean room class "100 000"

Operating conditions of the lamps

Geometrical conditions:

The lamps OSRAM WI41/G are aligned (see Fig. 4) without glowing:
- lamp's optical axis is central and rectangular to the filament plane
- lamp's optical axis is parallel to the bench's horizontal axis
- plane, containing lamp's optical axis and lamp axis (cap down) is vertical
- distance is measured from the centre of the filament
- only the light passing through the opening (see Fig. 4) in the mask is measured

For a measurement of the luminous intensity values the assigned distances vary depending on the effective location of the beginning of the light path within the filament of the lamps. Therefore, at PTB all luminous intensity measurements were carried out in a (large) distance of 5.5 m between the plane associated with the filament and the limiting aperture of the photometer. In most cases additional readings at reduced distances were taken to find out the sensitivity coefficient for a translation in the direction of the bench's optical axis. These coefficients are used for the evaluation of uncertainty as well as for a correction between the different measurements conditions, if needed. However, it turns out - as expected - that the influence is negligible under the conditions realized at PTB (distances 3 m to 7 m and apertures 10 mm to 30 mm in diameter; which corresponds to solid angels between $1.6 \cdot 10^{-6}$ sr and $79 \cdot 10^{-6}$ sr).

Electrical power supply and measurements:

The lamps are operated with constant DC-currents and the values are selected for a distribution temperature of about 2800 K. Every individual lamp is operated for a period of 15 minutes at nominal current before the measurement starts to warm up and to allow for the stabilization of its luminous output.

- the quantity to be set is constant DC current
- **negative polarity connected to central contact**
- lamp voltage is measured with two separate contacts, "four-pole-technique".

Stray-light reduction

The room for the measurements is divided by the rolling gate in two parts, one room for the lamp and a second room for measurement with the photometer bench (see Fig.3) ensuring large distances to the walls, ceiling and the floor. All sources of light except the lamp standard are switched off during measurement.
A light trap more than 1 m behind the lamp reduces the back reflected stray light. Baffles with various openings are placed on the photometer bench such that light illuminates neither the rails nor the room for measurements. The Fig. 6 gives an impression how baffles look like and are placed.
The land of a baffle if illuminated originates a relative stray-light of 10^{-5} which is corrected numerically. The box with the photometer carousel screens the photometer heads from any side-direction and a baffle with adjustable opening limits the field of view for the photometers. The illuminated entrance window of the photometer head reflects back and would illuminate the lamp. This is avoided by a minimal tilting just to direct the spot onto the baffles in between.

Fig. 6: Baffles with variable openings and flexible locations for stray-light reduction on the Photometer bench. The coating is diffuse and spectrally neutral reflecting with maximum reflectance of 5%.

Traceability chain and date of last realization

The luminous intensity unit at PTB is realized annually. The last realization was carried out in December 2013. The traceability chain at PTB (see Fig. 7) starts with the cryogenic radiometer to establish the unit of spectral radiant power, which is used to determine the spectral power responsivity of trap detectors. Using a uniform source based on tunable lasers and trap detectors with precision apertures, the responsivity with respect to optical power is transferred into a spectral irradiance resonsivity, and, in a second step, using $V(\lambda)$-corrected photometers, into the photometric responsivity. Parallel to this step, filtered detectors are calibrated to determine the temperature of a high temperature Black-Body radiator, used to provide the relative spectral distribution of transfer standard lamps at Illuminant A. Using the photometric bench system at PTB, the photometric responsivity of the calibrated photometers and the relative spectral distribution of the transfer standard lamps are combined to verify and establish the SI base unit Candela at PTB.

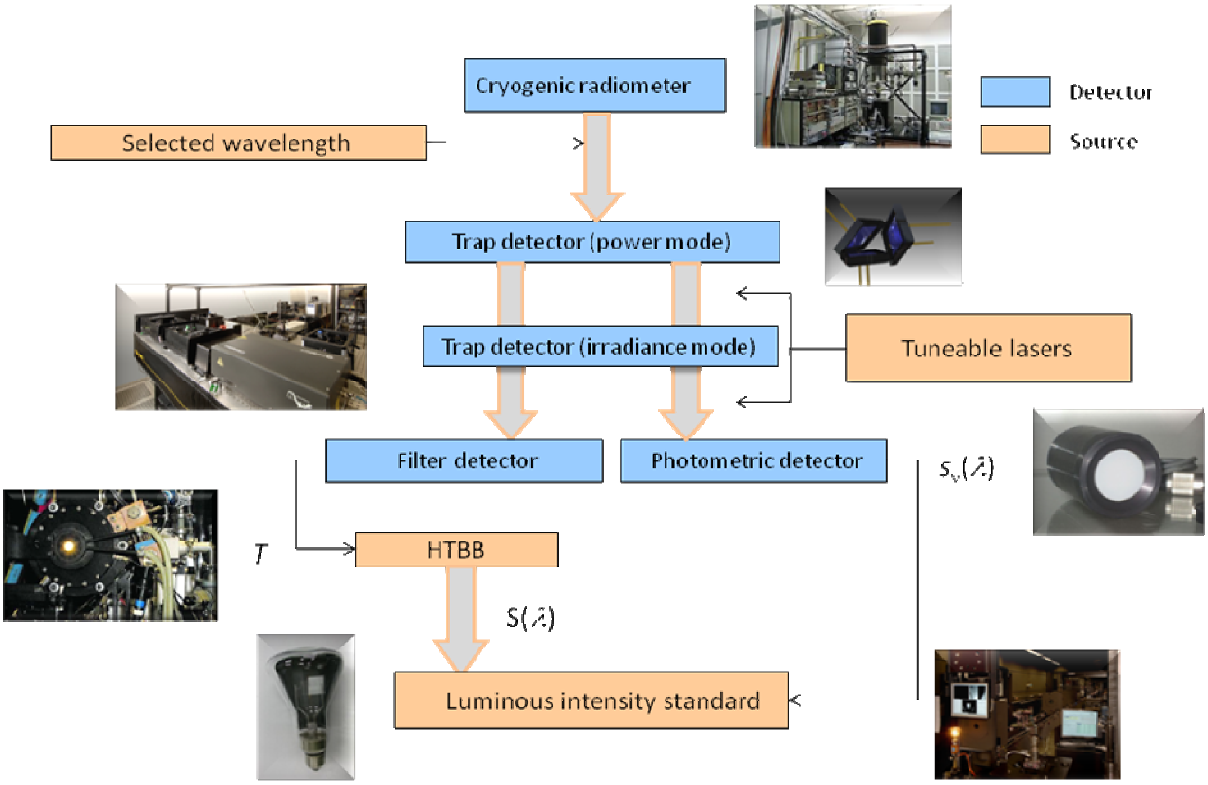


Fig. 7: Traceability chain at PTB

Parallel to this realization of the Candela, the unit Candela is also maintained at PTB since introduction of the new definition of the Candela in 1979 using a set of 17 Toshiba lamps operating at a distribution temperature of 2042 K, a set of 5 Toshiba lamps at 2353 K and 6 OSRAM WI41/G at 2600 K, and additional 12 OSRAM WI41/G lamps separated in two groups working at a distribution temperature of 2800 K, close to CIE-Illuminant A (see Fig. 8).

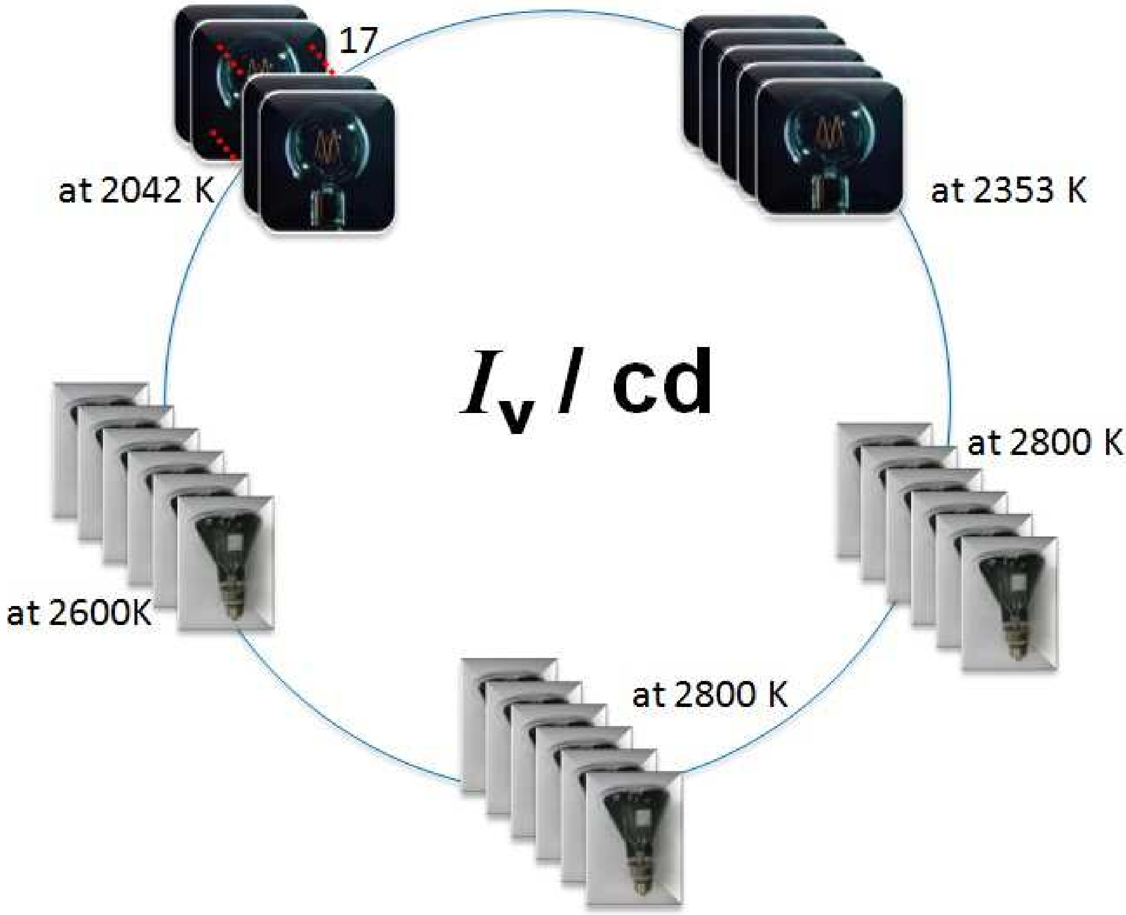


Fig. 8: Maintenance of the unit Candela by the luminous intensity lamps operated at various distribution temperatures.

Due to the different but very low aging rates of the various groups of lamps, which are only operated for traceability check once a year, the uncertainty of the preserved magnitude of the unit defined by this network of lamp groups is well below $1\cdot10^{-3}$ (k = 1). The preserved quantity, together with the realized quantity via the detector based traceability chain finally establish official magnitude of the unit Candela of PTB with an uncertainty of $1.02\cdot10^{-3}$ (k = 1). The magnitude of the unit is then disseminated by PTB by transfer standard lamps and transfer standard detectors with an uncertainty of typically $3.6\cdot10^{-3}$ (k = 2).

References:

[1] Erb, W., Sauter, G., *PTB network for realization and maintenance of the candela*, Metrologia, 1997, 34, 115-124

[2] Georg Sauter, Detlef Lindner, Matthias Lindemann, *CCPR Key Comparisons K3a of Luminous Intensity and K4 of Luminous Flux with Lamps as Transfer Standards,* PTB Bericht, PTB-Opt-62, 1999.

Appendix A.5

Uncertainty Budget (Example)

Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

The following example of the complete measurement budget is based on the document "CIE 198-SP1:2011". The explanations for all entries are given in that document and the values are taken out of the quality management system of the photometry laboratory except those which are found from the measurement of the individual lamps. The measurement uncertainty in line 35 is stated as standard measurement uncertainty. It has been determined in accordance with the "Evaluation of measurement data – Guide to the Expression of Uncertainty in Measurement; JCGM 100:2008".

CIE E 13 Calibration of a luminous intensity standard (source based) — manual entries are blue colored

Model

$$corS1 = \left(1 + 2\,\Delta d_{S1}/d_{PS} + \alpha_{S1}\,\Delta T_{aS1} + h_{S1}(\vartheta_{S1}) + k_{S1}(\varphi_{S1}) - \gamma_{S1}\,\Delta t_{S1}\right)$$

$$corSR = \left(1 + 2\,\Delta d_{SR}/d_{PS} + \alpha_{SR}\,\Delta T_{aSR} + h_{SR}(\vartheta_{SR}) + k_{SR}(\varphi_{SR}) - \gamma_{SR}\,\Delta t_{SR}\right)$$

$$I_{CS1} = I_{CSR}\,\frac{y_{PS1}}{y_{PSR}}\left(\frac{T_{dC1}}{T_{dCR}}\right)^{m_P}\left(\frac{c_J \cdot U_{JS1}}{J_{C1}\cdot R_J}\right)^{m_P\cdot mT_{S1} - mI_{S1}}\left(\frac{c_J \cdot U_{JSR}}{J_{CR}\cdot R_J}\right)^{-m_P\cdot mT_{SR} + mI_{SR}}\frac{corSR}{corS1}$$

No	Quantity X_i	Symbol	Value x_i	Abs. stand. uncertainty $u(x_i)$	Type	DOF ν_i	Absolute sensitivity c_i	Absolute contribution $u_i(y)$	Relative contribution $u_{rel}(y)$
1	amb.temp. difference [°C]	ΔT_{aS1}	0.0	0.50	B	50	0.0002	0.00010	0.00010
2	rel.temp.coeff. [1/K]	α_{S1}	0.0002	0.00020	B	∞	0.0000	0.00000	0.00000
3	angular tilt [1]	$h_{S1}(\vartheta_{S1})$	0.0	0.00089	B	∞	1.0000	0.00089	0.00089
4	angular turn [1]	$k_{S1}(\varphi_{S1})$	0.0	0.00020	B	∞	1.0000	0.00020	0.00020
5	relative distance variation [1]	$\Delta d_{S1}/d_{PS}$	0.0	0.00030	B	∞	2.0000	0.00060	0.00060
6	rel.aging coeff. [1/h]	γ_{S1}	0.0003	0.00020	B	∞	-0.1000	-0.00002	-0.00002
7	burning time [h]	Δt_{S1}	0.10	0	B	∞			
8	**correct. factor source [1]**	$corS1$	**1.0000**			**14641000**		**0.0011**	**0.0011**
9	amb.temp. difference REF [°C]	ΔT_{aSR}	0.0	0.5	B	50	0.00025	0.00012	0.00012
10	rel.temp.coeff. REF [1/K]	α_{SR}	0.00025	0.00025	B	∞	0.00000	0.00000	0.00000
11	angular tilt REF [1]	$h_{SR}(\vartheta_{SR})$	0.0	0.00020	B	∞	1.00000	0.00020	0.00020
12	angular turn REF [1]	$k_{SR}(\varphi_{SR})$	0.0	0.00010	B	∞	1.00000	0.00010	0.00010
13	relative distance variation REF [1]	$\Delta d_{SR}/d_{PS}$	0.0	0.00010	B	∞	2.00000	0.00020	0.00020
14	rel.aging coeff. REF [1/h]	γ_{SR}	0.00005	0.000050	B	∞	-0.10000	0.00000	0.00000
15	burning time REF [h]	Δt_{SR}	0.10	0	B	∞			
16	**correct. factor source REF [1]**	$corSR$	**1.0000**			**50568**		**0.00032**	**0.00032**
17	correction factor source REF [1]	$corSR$	1.0000	0.00032	A	1000	238.49	0.07632	0.00032
18	correction factor photometer [1]	$corS1$	1.0000	0.0011	A	1000	-238.50	-0.26235	-0.001
19	luminous intensity REF [cd]	I_{CSR}	14.756	0.0150	B	∞	16.1624	0.24244	0.00102
20	mean value photometer signal [V]	y_{PS1}	4.22128	0.00040	A	15	56.498	0.02260	0.000
21	mean value photometer signal [V]	y_{PSR}	0.25951	0.000070	A	15	-919.008	-0.06433	-0.00027
22	mean value current [V]	U_{JS1}	0.565030	0.000026	A	30	-2833.72	-0.07368	-0.000
23	mean value current REF [V]	U_{JSR}	0.536020	0.000025	A	30	3076.43	0.07691	0.00032
24	current intensity exponent [1]	mI_{S1}	6.70	0.30	B	∞	0.0181	0.00543	0.000
25	current intensity exponent REF [1]	mI_{SR}	6.90	0.20	B	∞	-0.0219	-0.00437	-0.00002
26	current distrib. temp exponent [1]	mT_{S1}	0.68	0.10	B	∞	0.0004	0.00004	0.000
27	current distrib. temp exp. REF [1]	mT_{SR}	0.72	0.20	B	∞	-0.0004	-0.00009	0.00000
28	distrib. temperature source [K]	T_{dC1}	2800	20	B	∞	-0.0017	-0.03407	-0.000
29	distrib. temperature REF [K]	T_{dCR}	2042	10	B	∞	0.0023	0.02336	0.00010
30	shunt resistor current [ohm]	R_J	0.1000129	0.000003	B	∞	-478.83	-0.00144	-0.00001
31	cal. factor current DVM [1]	c_J	1.0000	0.000048	B	∞	47.889	0.00230	0.00001
32	mismatch index [1]	m_P	-0.020	0.0025	B	∞	75.2929	0.18823	0.00079
33	nominal current of source [A]	J_{C1}	5.6500	0					
34	nominal current source REF [A]	J_{CR}	5.3600	0					0.001
35	**intensity at nom. Current [cd]**	I_{CS1}	**238.492**			**4232**		**0.43**	**0.00180**
			found from approximation formula: k =			**2.00**		**0.9**	**0.0036**
							variance	$u_{dev}(y) =$	0.12
							variance	$u_{inst}(y) =$	0.14%

Note:
The type A/B evaluation of uncertainties valid for the different quantities is stated above.

PTB-Answers

to the document CCPR-K3.2014_PDA_P2R1 from 2016-April-13

General Comment 1:

Straylight created by baffles in the light path depends strongly on their shapes and the construction of the edges and it is not corrected by background subtraction. This yields similarly for straylight back reflected from the light trap behind the lamp. The effect of this type of straylight is mostly compensated if luminous intensity lamps are used as reference standards for the transfer standards within the CCPR comparison as performed by the PTB. Provided this type of straylight contributes significantly to the combined uncertainty then it has to be mentioned in the model of evaluation and in the uncertainty budget. It should be mentioned that the baffles used at the PTB create a relative straylight $< 5 \cdot 10^{-5}$. In case the photometer is reference for the calibration of the luminous intensity standard lamps the uncertainty of the aperture has to be taken into account and only then the given reference [Metrologia **37**, 621 (2000)] is helpful.

General Comment 2:

Usually the photometer´s aperture plane is aligned by help of a mirror and a back reflected laser beam and any deviation from the perpendicular direction has to be weighted by the cosine. The effect of this misalignment is mostly compensated if the mounting of the photometer was unchanged between its calibration as reference and the transfer to the transfer standards within the CCPR comparison. Provided this misalignment contributes significantly to the combined uncertainty then it has to be mentioned in the model of evaluation and in the uncertainty budget.

General Comment 3:

In the Technical Protocol for this CCPR comparison chapter 6.1.1 the GUM is explicitly claimed as reference for any statement of measurement uncertainty. Additionally, the chapter 6.1.2 refers to the document CIE 198 as example for modeling combination and presentation. The protocol itself gives in Appendix A.5 an example for an abbreviated presentation. Thus, the model of evaluation is an essential part in the documentation and has to be stated individually by each participant as well as the complete uncertainty budget from CIE 198 as an intermediate step for the summarized presentation recommended in Appendix A.5 to simplify the comparison of individual contributions.

Questions to PTB:

a) According to the GUM all entries in Appendix A.5 are labeled in column 6 with "A" for "statistical" or "B" for any "other determination". These types of entries are combined and listed separately for each lamp. The list was send to the pilot for an additional explanation and mean values u(A) = 0.12% and u(B) = 0.13% are indicated. Thus, the combined standard uncertainty for the transfer by only one lamp is $u(I) = \sqrt{u(\mathrm{A})^2 + u(\mathrm{B})^2} = 0.18\%$.

b) At the bottom of the table Appendix A.5 two values labeled u_{dev} = 0.12% for random ("dev" for devise) and u_{inst} = 0.14% for systematic contributions ("inst" for instrumentation) are included. These numbers, their meaning and the evaluation are explained in all details in the publication CIE 198-SP1.2:2011 (see chapter/example 2.13). The combination of these numbers to determine the uncertainty of the whole batch for the transferred value of intensity is explained in great detail in CIE 198-SP1.1:2011 example 1.11.

It turns out that the instrumentation for the two rounds at PTB was stable and the properties of the PTB-transfer-standards (WI41/G) are uniform. A separation in types A and B or "random" and "systematic" gives no real difference. So, the uncertainty u(PTB) associated with the luminous intensity value transferred by **the batch** with a number of 6 PTB-transfer standards will be determined by the pilot laboratory from

$$u(I)_{\mathrm{PTB}} = \sqrt{u_{\mathrm{inst}}^2 + \frac{u_{\mathrm{dev}}^2}{6}} = 0.15\%$$

Braunschweig, 2016-April-28

2

Appendix A.6

Initial & Return measurement at PTB

Lamp-No.: 759

- Final result -

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Designation	Symbol	Initial measurement result (*as already reported in March 2014*)
Lamp current nominal value	J_L	5.65000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	29.1225 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2800 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	236.21 cd 0.18 %

Measurement at Pilot-Laboratory, operating time: 55 min

Designation	Symbol	Return measurement result (*June 2015*)
Lamp current nominal value	J_L	5.65000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	29.1225 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2800 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	236.22 cd 0.18 %

Operating time at PTB: 37 min

Note: The stated results of the return measurements at PTB include the aging corrections for the total operating time at the Pilot-Laboratory and at the PTB using the following averaged relative correction coefficients with associated standard uncertainties:

Lamp voltage +6.0E-5/h with 3.0E-5/h
Luminous intensity +2.5E-4/h with 1.0E-4/h

Appendix A.6

Initial & Return measurement at PTB

Lamp-No.: 791

- Final result -

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Designation	Symbol	Initial measurement result (*as already reported in March 2014*)
Lamp current nominal value	J_L	5.65000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	29.5643 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2800 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	247.55 cd 0.18 %

Measurement at Pilot-Laboratory, operating time: 55 min

Designation	Symbol	Return measurement result (*June 2015*)
Lamp current nominal value	J_L	5.65000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	29.5649 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2800 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	247.53 cd 0.18 %

Operating time at PTB: 38 min

Note: The stated results of the return measurements at PTB include the aging corrections for the total operating time at the Pilot-Laboratory and at the PTB using the following averaged relative correction coefficients with associated standard uncertainties:
Lamp voltage +6.0E-5/h with 3.0E-5/h
Luminous intensity +2.5E-4/h with 1.0E-4/h

Appendix A.6

Initial & Return measurement at PTB

Lamp-No.: 793

- Final result -

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Designation	Symbol	Initial measurement result (*as already reported in March 2014*)
Lamp current nominal value	J_L	5.65000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	29.3866 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2800 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	245.97 cd 0.18 %

Measurement at Pilot-Laboratory, operating time: 52 min

Designation	Symbol	Return measurement result (*June 2015*)
Lamp current nominal value	J_L	5.65000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	29.3867 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2800 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	246.00 cd 0.18 %

Operating time at PTB: 36 min

Note: The stated results of the return measurements at PTB include the aging corrections for the total operating time at the Pilot-Laboratory and at the PTB using the following averaged relative correction coefficients with associated standard uncertainties:

Lamp voltage +6.0E-5/h with 3.0E-5/h
Luminous intensity +2.5E-4/h with 1.0E-4/h

Appendix A.6

Initial & Return measurement at PTB
Lamp-No.: 848
- Final result -

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Designation	Symbol	Initial measurement result (*as already reported in March 2014*)
Lamp current nominal value	J_L	5.70000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	28.5727 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2810 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	228.53 cd 0.18 %

Measurement at Pilot-Laboratory, operating time: 53 min

Designation	Symbol	Return measurement result (*June 2015*)
Lamp current nominal value	J_L	5.70000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	28.5712 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2810 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	228.54 cd 0.18 %

Operating time at PTB: 34 min

Note: The stated results of the return measurements at PTB include the aging corrections for the total operating time at the Pilot-Laboratory and at the PTB using the following averaged relative correction coefficients with associated standard uncertainties:
Lamp voltage +6.0E-5/h with 3.0E-5/h
Luminous intensity +2.5E-4/h with 1.0E-4/h

Appendix A.6

Initial & Return measurement at PTB

Lamp-No.: 851

- Final result -

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Designation	Symbol	Initial measurement result (*as already reported in March 2014*)
Lamp current nominal value	J_L	5.70000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	28.9316 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2815 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	233.49 cd 0.18 %

Measurement at Pilot-Laboratory, operating time: 57 min

Designation	Symbol	Return measurement result (*June 2015*)
Lamp current nominal value	J_L	5.70000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	28.9313 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2815 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	233.54 cd 0.18 %

Operating time at PTB: 34 min

Note: The stated results of the return measurements at PTB include the aging corrections for the total operating time at the Pilot-Laboratory and at the PTB using the following averaged relative correction coefficients with associated standard uncertainties:
Lamp voltage +6.0E-5/h with 3.0E-5/h
Luminous intensity +2.5E-4/h with 1.0E-4/h

Appendix A.6

Initial & Return measurement at PTB
Lamp-No.: 858
- Final result -

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Designation	Symbol	Initial measurement result (*as already reported in March 2014*)
Lamp current nominal value	J_L	5.70000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	28.5610 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2800 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	225.12 cd 0.18 %

Measurement at Pilot-Laboratory, operating time: 54 min

Designation	Symbol	Return measurement result (*June 2015*)
Lamp current nominal value	J_L	5.70000 A
Lamp voltage value relative standard uncertainty	U_L $u_{rel}(U_L)$	28.5618 V 0.011 %
Distribution temperature value absolute standard uncertainty	T_d $u(T_d)$	2800 K 20 K
Luminous intensity value relative standard uncertainty	I $u_{rel}(I)$	225.01 cd 0.18 %

Operating time at PTB: 35 min

Note: The stated results of the return measurements at PTB include the aging corrections for the total operating time at the Pilot-Laboratory and at the PTB using the following averaged relative correction coefficients with associated standard uncertainties:
Lamp voltage +6.0E-5/h with 3.0E-5/h
Luminous intensity +2.5E-4/h with 1.0E-4/h

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>VNIIOFI Report</u>

Appendix A.3 Description of the VNIIOFI measurement facility

The items listed on this form should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated on this page. Please expand your reply document as necessary.

Description of measurement geometry (please include a diagram):

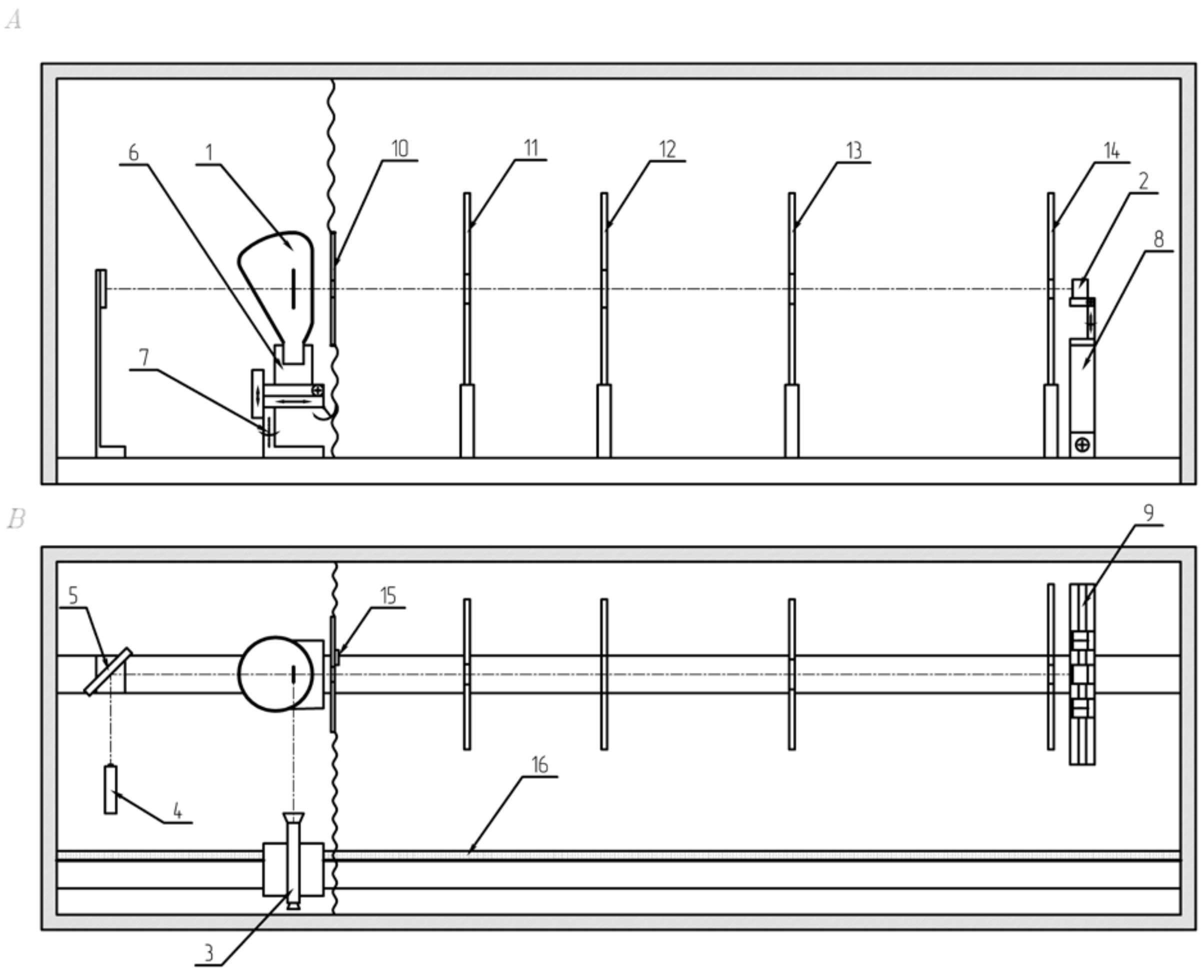


Fig.1. Diagram of VNIIOFI facility used for measuring luminous intensity of comparison lamps within the CCPR-K3.2014 comparison. A – side view; B – top view. 1 – lamp to be measured; 2 – photometer; 3 – telescope; 4 – alignment laser; 5 – mirror; 6 – lamp socket; lamp alignment mount; photometer alignment mount; translation stage; 10 - limiting baffle (aperture is 40x45 mm); 11 – baffle with shutter (aperture is 55x80 mm); 12 – baffle with aperture diameter of 100 mm; 13 – baffle with aperture diameter of 80 mm; 14 – baffle with aperture diameter of 50 mm; 16 – ruler.

- positions of lamp, detector, bench, shielding, baffles (number, distances and sizes)

A lamp, photometers and baffles stand on a rail inside a light-tight box. On a parallel rail there is a telescope for aligning a lamp and measuring distance. All side walls of the box are covered with black velvet cloth. The ceiling and baffles are painted by diffuse black paint.

Three photometers were used for the comparison. All three were located on a translation stage perpendicular to the rail. The photometers were pre-aligned before the measurements and then replaced each other without additional alignment during the measurement.

A laser beam, reflected by a mirror behind the lamp, is used for aligning the lamp and photometers. The distance from the lamp to the mirror is 550 mm. During measurements the laser and mirror are shielded by black velvet cloth.

The lamp area is separated from the other box volume by a black velvet curtain. In the plain of the curtain in front of the lamp filament there is a limiting baffle. The distance between the baffle and the lamp bulb is 50 mm. The aperture of the baffles is rectangular 40x45 mm (width x height).

There are four additional baffles between the lamp curtain and the photometers. The widths and heights of the baffles are 400 mm and 510 mm, respectively. Aperture of the baffle nearest to the curtain is rectangular of 55x80 mm. This baffle is equipped with a shutter. Apertures of other baffles are round with diameters of (if counted from the lamp to the photometer): 100 mm, 80 mm and 50 mm. The distances: from the curtain to the first baffle is 320 mm; from the first to the second is also 320 mm; from the second to the third is 500 mm; from the photometer to the fourth is 50 mm.

- alignment devices A laser and a telescope
- solid angle of luminous intensity measurements:
  - distance of photometer from lamp Approximately 2100 mm
  - size of photometer input aperture Round with diameter of 15 mm
- limiting aperture? 40x45 mm (width x height) at the distance of approximately 2050 mm from the photometer (about 50 mm from the lamp bulb).

Description of measurement procedures.

Four (at least) independent measurement were done for each lamp with total re-alignment of photometers and lamps. Each independent measurement comprised the following steps:

1) Aligning the photometers using a laser beam;
2) Screwing a lamp into a holder and aligning the lamp;
3) Measuring distance between the lamp and photometers;
4) Turning on the lamp, putting the set current; waiting for 15 minutes;
5) Checking the current, measuring the lamp voltage;
6) Measuring photocurrent of the first photometer, then closing the stutter and measuring the dark current. 25 reading were taken for both “light” current and dark current;
7) Replacing the photometer and in turn measuring photocurrent and dark of the second and third photometers;
8) Turning off the lamp. Replace the lamp. Repeat 2) – 7) for all lamps.

Make and type of the photometer (or equivalent). LMP Photometerhead of the **P150T** type with LMT photocurrent meter of the **I1000** type

Operating conditions of the lamps:

- geometrical alignment
  - definitions of defined point and reference plane at the lamp
    - for Osram lamps with center filament supports, which center filament support type is used for the alignment (see Figure Two and Section 4.4.8.)
      We used the type called “Center Filament Support #1”
  - alignment procedure
    - is the filament at room temperature or glowing for the alignment?

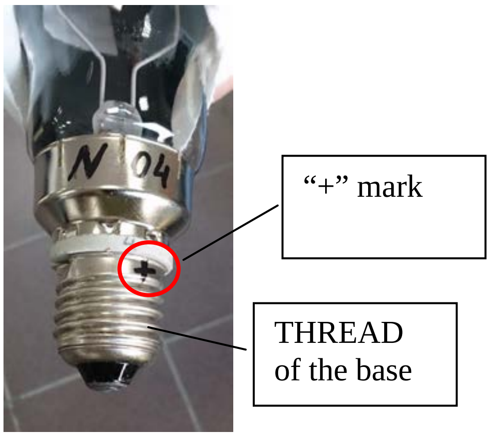
At room temperature

- alignment jig? If so, how is it used? No jig was used.
- size and position of limiting aperture

40x45 mm (width x height) at the distance of approximately 2050 mm from the photometer (about 50 mm from the lamp bulb). This aperture is smaller that the lamp window.

- electrical polarity, current, voltage for each traveling standard

Positive polarity on the thread of the lamp base:



Lamp #	Current, A	CCT, K	Voltage, V
N 01	5,880	2855,8	**30.419**
N 02	5,900	2854,1	**30.647**
N 03	5,920	2853,6	**30.594**
N 04	5,870	2856,6	**30.487**
3281	5,880	2853,9	**29.952**
3282	5,800	2854,3	**30.547**

- length of warm-up time for each lamp before measurements are taken

15 minutes

- measured CCT (or Distribution Temperature or Colour Temperature, see Section 3.5).

See the table above

- stray-light reduction

No correction for stray-light was done

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

Temperature varied from 21.8 ºC to 23 ºC during the first round and from 21.4 ºC to 22.6 ºC during the second round

Humidity was about 30% during the first round, but did not measured during the second one.

Laboratory transfer standards used:

- type of transfer standards and traceability to primary scale

  Three photometers of LMT **P150T** type, # 31, #32 and #131.

Establishment or traceability route of primary scale including date of last realisation and uncertainty budget.

Primary scale was realized using a high-temperature blackbody. Luminous intensity of the blackbody calculated as

$$I_{\mathrm{BB}} = \varepsilon \cdot A \cdot K_{\mathrm{cd}} \cdot \int L_{\lambda,\mathrm{BB}}(\lambda, T_{\mathrm{BB}}) \cdot V(\lambda) d\lambda \qquad (1)$$

where
K_{cd} is the luminous efficacy, equals to 683 cd·sr/W
$V(\lambda)$ is the photopic luminous efficiency function,
$L_{\lambda,\mathrm{BB}}(\lambda, T_{BB})$ is the ideal blackbody spectral radiance,
T_{BB} is the blackbody temperature,
ε is the blackbody emissivity and
A is an area of the blackbody aperture.

The temperature of the blackbody was approximately 2856 K. The exact temperature was measured by a radiation thermometer, which was calibrated against three high-temperature fixed points: Co-C (1597 K), Re-C (2748 K) and WC-C (3021 K). The fixed points were earlier measured by means of comparison with the copper fixed point (1357.77 K) in according with the ITS-90. The standard uncertainty of blackbody temperature measurement was 0.5 K.

The emissivity of the blackbody was estimated using the Monte-Carlo based software STEEP3. as 0.9995 with standard uncertainty of 0.0002.

A water-cooled bronze aperture was used with approximate diameter of 8 mm. The exact value of an average diameter measure with standard uncertainty of 1.5 μm.

Responsivities of the photometers to the Type A source were measured against the blackbody and equals:

$$s_{\mathrm{v,phot}} = \frac{i_{\mathrm{phot}}}{g \cdot \left(I_{\mathrm{BB}} / l^2\right)} \cdot M \qquad (2)$$

where

$$M = \frac{\int L_{\lambda,\mathrm{BB}}(\lambda, T_{\mathrm{A}}) \cdot s_{\mathrm{rel,phot}}(\lambda) d\lambda}{\int L_{\lambda,\mathrm{BB}}(\lambda, T_{\mathrm{A}}) \cdot V(\lambda) d\lambda} \cdot \frac{\int L_{\lambda,\mathrm{BB}}(\lambda, T_{\mathrm{BB}}) \cdot V(\lambda) d\lambda}{\int L_{\lambda,\mathrm{BB}}(\lambda, T_{\mathrm{BB}}) \cdot s_{\mathrm{rel,phot}}(\lambda) d\lambda} \qquad (3)$$

M – Spectral mismatch correction factor;
$s_{\mathrm{rel,phot}}(\lambda)$ – Relative spectral responsivity of the photometer;
T_{A} = 2856 K;
l – Distance between the photometer and the blackbody aperture was about 720 mm;
g – Geometry correction depends on sizes of apertures and the distance.

Because the temperature of the blackbody agreed with T_{A} = 2856 K within 2K only, the difference of M from the unit and its uncertainty were negligible (less than 0.005%).

Uncertainty budget of the photometer calibration:

Source of uncertainty	Luminous Intensity standard uncertainty, %
Blackbody temperature (0.5 K)	0.16
Blackbody uniformity	0.03
Blackbody stability (0.03 K)	0.01
Emissivity	0.02
Aperture size (1.5 µm)	0.04
Distance (0.1 mm)	0.03
Stray light	0.04
Repeatability of measurement (with independent alignment)	0.08
Combined Standard Uncertainty	0.19

The last realization and calibration of the photometers was done in December 2013 (one month before the first round measurements of the K3 lamps).

Contact person: Boris Khlevnoy

NMI: VNIIOFI

Date: 25 November 2015

Signature:

Appendix A.4 Record of lamp operating time

Lamp number: N 01

Date	Lamp ON time	Activity/Comments (test. alignment. measurement)	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
Preliminary total burn time of the lamp was about 2 hour							
26.12.13	12:15	Annealing	18:05	5:50	5.890	30.613	CCK
27.12.13	09:00	Annealing	15:15	6:15	5.890	30.607	CCK
13.01.14	11:00	CCT measurement	13:55	2:55	5.8520	30.238	CCK
14.01.14	11:00	CCT measurement	13:20	2:20	5.8700	30.412	CCK
29.01.14	11:10	Measurement	11:50	0:40	5.8800	30.420	EBM
30.01.14	15:50	Measurement	16:30	0:40	5.8800	30.420	EBM
04.02.14	14:12	Measurement	14:52	0:40	5.8800	30.420	EBM
07.02.14	10:43	Measurement	11:18	0:35	5.8800	30.417	EBM
17.02.14	15:22	Measurement	15:46	0:24	5.8800	30.418	EBM
30.03.15	14:10	Measurement	14:38	0:28	5.8800		EBM
31.03.15	13:37	Measurement	14:07	0:30	5.8800		EBM
01.04.15	13:43	Measurement	14:13	0:30	5.8800	30.413	EBM
02.04.15	16:20	Measurement	16:50	0:30	5.8800	30.414	EBM

Participant: VNIIOFI (Russia)

Date: 27.11.2015

Signature: /Boris Khlevnoy/

Appendix A.4 Record of lamp operating time

Lamp number: N 02

Date	Lamp ON time	Activity/Comments (test. alignment. measurement)	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
Preliminary total burn time of the lamp was about 2 hour							
26.12.13	12:40	Annealing	18:05	5:35	5.900	30.753	CCK
27.12.13	09:15	Annealing	15:15	6:00	5.900	30.737	CCK
13.01.14	14:15	CCT measurement	16:20	2:05	5.8950	30.686	CCK
29.01.14	13:30	Measurement	14:08	0:38	5.9000	30.650	EBM
31.01.14	11:15	Measurement	11:50	0:35	5.9000	30.646	EBM
04.02.14	11:03	Measurement	11:38	0:35	5.9000	30.645	EBM
07.02.14	13:48	Measurement	14:21	0:27	5.9000	30.646	EBM
30.03.15	14:50	Measurement	15:20	0:30	5.9000		EBM
31.03.15	14:20	Measurement	14:52	0:32	5.9000		EBM
01.04.15	14:25	Measurement	14:55	0:30	5.9000	30.638	EBM
03.04.15	10:07	Measurement	10:37	0:30	5.9000	30.635	EBM

Participant: VNIIOFI (Russia)

Date: 27.11.2015

Signature: /Boris Khlevnoy/

Appendix A.4 Record of lamp operating time

Lamp number: N 03

Date	Lamp ON time	Activity/Comments (test. alignment. measurement)	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
Preliminary total burn time of the lamp was about 2 hour							
30.12.13	10:00	Annealing	15:45	5:45	5.880	30.321	CCK
09.01.14	10:35	Annealing	17:10	6:35	5.880	30.304	CCK
14.01.14	13:55	CCT measurement	17:00	3:05	5.9140	30.627	CCK
29.01.14	14:30	Measurement	15:08	0:38	5.9200	30.600	EBM
31.01.14	13:23	Measurement	14:00	0:37	5.9200	30.595	EBM
03.02.14	16:20	Measurement	16:55	0:35	5.9200	30.594	EBM
04.02.14	15:10	Measurement	15:50	0:40	5.9200	30.594	EBM
06.02.14	11:15	Measurement	11:55	0:40	5.9200	30.592	EBM
17.02.14	13:57	Measurement	14:40	0:43	5.9200	30.593	EBM
30.03.15	15:22	Measurement	15:57	0:35	5.9200		EBM
31.03.15	15:40	Measurement	16:12	0:32	5.9200		EBM
01.04.15	15:12	Measurement	15:42	0:30	5.9200	30.584	EBM
03.04.15	10:48	Measurement	11:16	0:28	5.9200	30.583	EBM

Participant: VNIIOFI (Russia)

Date: 27.11.2015

Signature:  /Boris Khlevnoy/

Appendix A.4 Record of lamp operating time

Lamp number: N 04

Date	Lamp ON time	Activity/Comments (test. alignment. measurement)	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
Preliminary total burn time of the lamp was about 2 hour							
30.12.13	10:00	Annealing	15:45	5:45	5.880	30.658	CCK
09.01.14	10:35	Annealing	17:10	6:35	5.880	30.668	CCK
15.01.14	11:35	CCT measurement	13:00	1:25	5.8600	30.477	CCK
30.01.14	11:10	Measurement	11:45	0:35	5.8700	30.487	EBM
31.01.14	14:25	Measurement	15:00	0:35	5.8700	30.486	EBM
03.02.14	14:35	Measurement	15:10	0:35	5.8700	30.490	EBM
06.02.14	14:35	Measurement	15:10	0:35	5.8700	30.487	EBM
30.03.15	16:13	Measurement	16:41	0:28	5.8700		EBM
31.03.15	16:30	Measurement	17:00	0:30	5.8700		EBM
01.04.15	16:15	Measurement	16:43	0:28	5.8700	30.485	EBM
03.04.15	13:10	Measurement	13:40	0:30	5.8700	30.485	EBM

Participant: VNIIOFI (Russia)

Date: 27.11.2015

Signature: /Boris Khlevnoy/

Appendix A.4 Record of lamp operating time

Lamp number: 3281

Date	Lamp ON time	Activity/Comments (test. alignment. measurement)	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
Preliminary total burn time of the lamp was about 2 hour							
26.12.13	12:10	Annealing	17:20	5:10	5.880	29.953	EBM
27.12.13	07:55	Annealing	13:00	5:05	5.880	29.946	EBM
10.01.14	11:45	CCT measurement	14:05	2:20	5.8750	29.996	CCK
28.01.14	11:10	Measurement	11:48	0:38	5.8800	29.952	EBM
28.01.14	14:10	Measurement	14:58	0:48	5.8800	29.951	EBM
30.01.14	13:30	Measurement	14:15	0:45	5.8800	29.951	EBM
03.02.14	10:53	Measurement	11:34	0:41	5.8800	29.953	EBM
05.02.14	11:30	Measurement	12:05	0:35	5.8800	29.951	EBM
30.03.15	10:45	Measurement	11:15	0:30	5.8800		EBM
31.03.15	10:20	Measurement	10:54	0:34	5.8800		EBM
01.04.15	11:28	Measurement	11:58	0:30	5.8800	29.944	EBM
02.04.15	13:52	Measurement	14:22	0:30	5.8800	29.943	EBM

Participant: VNIIOFI (Russia)

Date: 27.11.2015

Signature:  /Boris Khlevnoy/

Appendix A.4 Record of lamp operating time

Lamp number: 3282

Date	Lamp ON time	Activity/Comments (test. alignment. measurement)	Lamp OFF time	Burn time (hrs)	Lamp Current (amperes)	Lamp Voltage (volts)	Operator initials
Preliminary total burn time of the lamp was about 2 hour							
27.12.13	13:45	Annealing	18:20	3:35	5.800	30.548	EBM
09.01.14	10:40	Annealing	16:40	6:00	5.800	30.540	EBM
10.01.14	10:50	Annealing	13:50	3:00	5.800	30.535	EBM
10.01.14	14:25	CCT measurement	16:20	1:55	5.7900	30.543	CCK
28.01.14	16:10	Measurement	16:45	0:35	5.8000	30.547	EBM
30.01.14	14:35	Measurement	15:12	0:37	5.8000	30.547	EBM
03.02.14	13:45	Measurement	14:20	0:35	5.8000	30.551	EBM
06.02.14	15:30	Measurement	16:00	0:30	5.8000	30.546	EBM
30.03.15	13:30	Measurement	13:58	0:28	5.8000		EBM
31.03.15	11:10	Measurement	11:44	0:34	5.8000		EBM
01.04.15	11:12	Measurement	11:40	0:28	5.8000	30.541	EBM
02.04.15	14:35	Measurement	15:02	0:28	5.8000	30.542	EBM

Participant: VNIIOFI (Russia)

Date: 27.11.2015

Signature:  /Boris Khlevnoy/

Appendix A.5 Sample Measurement Uncertainty Budget

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of working standards		
- Photometers of LMT P150T type	B	0.19
Electrical		
- standard resistor	B	0.002
- voltmeter	B	0.07
Photometer		
- spectral mismatch	B	0.001
- linearity	B	0.01
- distance	B	0.05
Environment		
- stray light	B	**0.1**
- temperature / humidity	B	0.02
Lamp alignment (systematic component)	B	0.03
Discrepancy between photometers (systematic)	B	0.04
Stability of photometers*	B	0.07
RMS total systematic effects:		
1st Round		**0.24**
2nd Round		**0.25**
Random effects****:**		
Electrical parameters:		
- power supply fluctuations, u_{psf}	B	0.02
Photometer noise (25 readings), u_{noise}	A	0.001
Discrepancy between three photometers (random), u_{pd}	A	0.05
Independent measurement reproducibility *** , u_{rep}	A	0.05
RMS total random effects****:		**0.06**
RMS total standard uncertainty:		
1st Round		**0.25**
2nd Round		**0.26**

* For the second round only

** Standard deviations varied from set to set and from lamp to lamp. Typical values are presented in the table.

*** Each independent measurement was done with total re-alignment of a lamp and the photometers. Random effect associated with independent measurement reproducibility comprises several random effects: lamp alignment, photometer alignment, random error in distance measurement, lamp fluctuation.

**** Uncertainty associated with reproducibility (u_{rep}) partly includes uncertainties associated with other random effects. Therefore, the Total random uncertainty is calculated as

$$u_{Total,Random} = \sqrt{u_{\text{rep}}^2 + (u_{\text{pd}}^2 + u_{\text{noise}}^2 + u_{\text{psf}}^2)/n}$$

where n = 4 – the typical number of independent measurements

Measurement parameters given in this table are suggested. Please modify and itemize according to your particular situation. See Section 6.2 for explanation of the various items.

Note that if lamps are used as the laboratory working standards, a group of uncertainties would need to be included in the above table to account for their behaviour.

The RMS total refers to the usual square root of the sum of the squares of all the individual uncertainty terms.

Contact person: Boris Khlevnoy

NMI: VNIIOFI

Date: 25 November 2015

Signature:

NMI:	VNIIOFI										
Lamp#	**Measurement#**			**Date**	**Lamp Electrical**		**Lamp CCT**	**Luminous Intensity (cd)**			
	Round#	**Set#**	**Meas#PerSet**		**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Standard Uncertainty (%)**		
									Random	**Systematic**	**final**
3281	1	1	25	2014-Jan-28	5.8800	29.952	2853.9	273.23	0.05	0.22	
	1	2	25	2014-Jan-30	5.8800	29.951		273.33	0.05	0.22	
	1	3	25	2014-Feb-03	5.8800	29.953		273.88	0.05	0.22	
	1	4	25	2014-Feb-05	5.8800	29.951		273.50	0.05	0.22	
		Average			**5.8800**	**29.952**		**273.48**	**0.06**	**0.24**	**0.25**
	2	1	25	2015-Mar-30	5.8800			275.76	0.05	0.23	
	2	2	25	2015-Mar-31	5.8800			274.81	0.05	0.23	
	2	3	25	2015-Apr-01	5.8800	29.944		274.87	0.05	0.23	
	2	4	25	2015-Apr-02	5.8800	29.943		274.82	0.05	0.23	
		Average			**5.8800**	**29.943**		**275.06**	**0.06**	**0.25**	**0.26**
3282	1	1	25	2014-Jan-28	5.8000	30.547	2854.3	276.97	0.05	0.22	
	1	2	25	2014-Jan-30	5.8000	30.547		276.89	0.05	0.22	
	1	3	25	2014-Feb-03	5.8000	30.550		276.65	0.05	0.22	
	1	4	25	2014-Feb-06	5.8000	30.546		276.95	0.05	0.22	
		Average			**5.8000**	**30.547**		**276.87**	**0.06**	**0.24**	**0.25**
	2	1	25	2015-Mar-30	5.8000			277.07	0.05	0.23	
	2	2	25	2015-Mar-31	5.8000			277.24	0.05	0.23	
	2	3	25	2015-Apr-01	5.8000	30.541		276.70	0.05	0.23	
	2	4	25	2015-Apr-02	5.8000	30.542		276.49	0.05	0.23	
		Average			**5.8000**	**30.541**		**276.88**	**0.06**	**0.25**	**0.26**
N 01	1	1	25	2014-Jan-29	5.8800	30.419	2855.8	287.01	0.05	0.22	
	1	2	25	2014-Jan-30	5.8800	30.420		286.99	0.05	0.22	
	1	3	25	2014-Feb-04	5.8800	30.420		287.37	0.05	0.22	
	1	4	25	2014-Feb-07	5.8800	30.417		287.37	0.05	0.22	
		Average			**5.8800**	**30.419**		**287.19**	**0.06**	**0.24**	**0.25**
	2	1	25	2015-Mar-30	5.8800			286.77	0.05	0.23	
	2	2	25	2015-Mar-31	5.8800			286.26	0.05	0.23	
	2	3	25	2015-Apr-01	5.8800	30.413		286.75	0.05	0.23	
	2	4	25	2015-Apr-02	5.8800	30.414		286.38	0.05	0.23	
		Average			**5.8800**	**30.413**		**286.54**	**0.06**	**0.25**	**0.26**
N 02	1	1	25	2014-Jan-29	5.9000	30.650	2854.1	286.07	0.05	0.22	
	1	2	25	2014-Jan-31	5.9000	30.647		285.80	0.05	0.22	
	1	3	25	2014-Feb-04	5.9000	30.645		286.02	0.05	0.22	
	1	4	25	2014-Feb-07	5.9000	30.646		285.63	0.05	0.22	
		Average			**5.9000**	**30.647**		**285.88**	**0.06**	**0.24**	**0.25**
	2	1	25	2015-Mar-30	5.9000			285.61	0.05	0.23	
	2	2	25	2015-Mar-31	5.9000			284.89	0.05	0.23	
	2	3	25	2015-Apr-01	5.9000	30.638		285.39	0.05	0.23	
	2	4	25	2015-Apr-03	5.9000	30.635		284.85	0.05	0.23	
		Average			**5.9000**	**30.637**		**285.18**	**0.06**	**0.25**	**0.26**
N 03	1	1	25	2014-Jan-29	5.9200	30.600	2853.6	283.81	0.05	0.22	
	1	2	25	2014-Jan-31	5.9200	30.595		285.21	0.05	0.22	
	1	3	25	2014-Feb-03	5.9200	30.594		285.25	0.05	0.22	
	1	4	25	2014-Feb-04	5.9200	30.594		284.10	0.05	0.22	
		5	25	2014-Feb-06	5.9200	30.592		284.77	0.05	0.22	
		6	25	2014-Feb-17	5.9200	30.593		283.92	0.05	0.22	
		Average			**5.9200**	**30.594**		**284.51**	**0.06**	**0.24**	**0.25**
	2	1	25	2015-Mar-30	5.9200			283.73	0.05	0.23	
	2	2	25	2015-Mar-31	5.9200			284.04	0.05	0.23	
	2	3	25	2015-Apr-01	5.9200	30.584		283.64	0.05	0.23	
	2	4	25	2015-Apr-03	5.9200	30.583		283.35	0.05	0.23	
		Average			**5.9200**	**30.583**		**283.69**	**0.06**	**0.25**	**0.26**
N 04	1	1	25	2014-Jan-28	5.8700	30.487	2856.6	284.27	0.05	0.22	
	1	2	25	2014-Jan-30	5.8700	30.486		284.32	0.05	0.22	
	1	3	25	2014-Feb-03	5.8700	30.490		283.76	0.05	0.22	
	1	4	25	2014-Feb-05	5.8700	30.487		283.79	0.05	0.22	
		Average			**5.8700**	**30.487**		**284.04**	**0.06**	**0.24**	**0.25**
	2	1	25	2015-Mar-30	5.8700			284.23	0.05	0.23	
	2	2	25	2015-Mar-31	5.8700			284.11	0.05	0.23	
	2	3	25	2015-Apr-01	5.8700	30.485		284.23	0.05	0.23	
	2	4	25	2015-Apr-03	5.8700	30.485		283.62	0.05	0.23	
		Average			**5.8700**	**30.485**		**284.05**	**0.06**	**0.25**	**0.26**

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>NIST Report</u>

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899-

REPORT OF CALIBRATION

Luminous Intensity and Color Temperature Standard Lamps

Six incandescent lamps model Wi41/G manufactured by Osram Inc.
with the designations NIST20100, NIST20101, NIST20102, NIST20103,
NIST20104, and NIST20105

Submitted to:

National Research Council of Canada
Attn.: Dr. Arnold Gaertner
Measurement Science and Standards
1200 Montreal Road, Building M36
Ottawa, Ontario, Canada K1A 0R6

1. Calibration Item

Six incandescent lamps model Wi41/G manufactured by Osram Inc. were calibrated for correlated color temperature and for luminous intensity. The lamp designations NIST20100, NIST20101, NIST20102, NIST20103, NIST20104, and NIST20105 are marked on the lamp base.

2. Description of the Calibration

The luminous intensity measurement is based on the NIST detector-based candela scale realized in 2013 and 2015 and therefore on the international definition of the candela in effect since 1979. The color temperature measurement is based on the international temperature scale of 1990 (ITS-90). The details of the NIST luminous intensity unit and the color temperature scale are described in Section 3.1 and 7.2 of reference [1].

All Wi41/G lamps are operated with base down orientation as described in the CCPR-K3-2014 protocol. The center contact of the lamp base must be connected to the negative output terminal of a DC power supply. The alignment reference for NIST Wi41i/G lamps is slightly different as that described in the CCPR-K3-2014 protocol. The procedure below must be used to align the NIST Wi41/G lamps for measurement of luminous intensity. This procedure refers to the coordinate system described in the CCPR-K3-2014 protocol (Figure 1).

(1) Focus the end telescope on the filament. Rotate the lamp about X axis and adjust the lamp position along Y axis and Z axis so that the lamp filament is vertical and centered on the optical axis (as shown in Figure 2, the same procedure as that in the protocol).

Calibration Date: August 14, 2015
NIST Test No.: 2015CCPR-K3-F

REPORT OF CALIBRATION
Luminous Intensity and Color Temperature Calibration
National Research Council of Canada

Manufacturer: Osram
Model: Wi41/G
Designation: NIST20100, NIST20101, NIST20102, NIST20103, NIST20104, and NIST20105

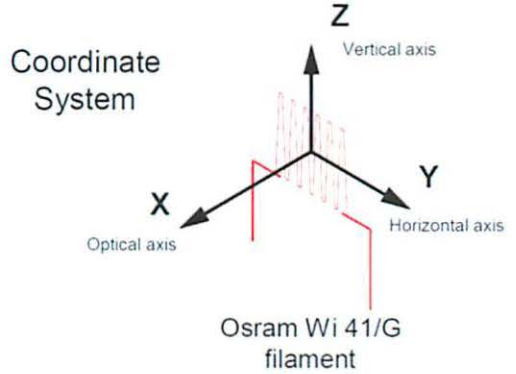


Figure 1 – Lamp filament and coordinate system, shown with the Osram Wi41/G filament

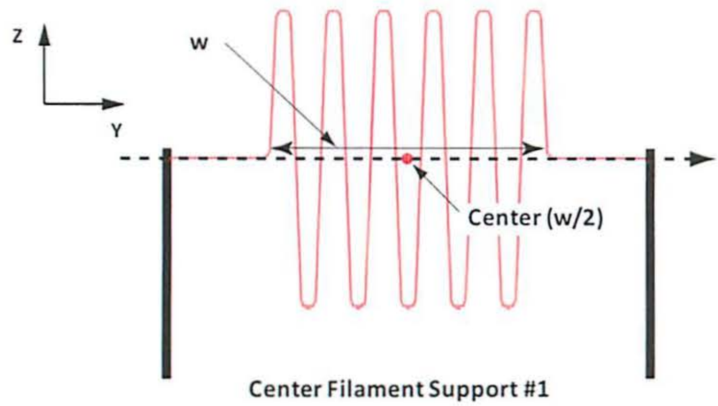


Figure 2 - Osram Wi41/G filament defined point: Center

(2) Focus the side telescope on the right filament post (viewing the lamp from the photometer). Rotate the lamp about Y axis and adjust the lamp position along X axis so that the right filament post is aligned exactly on the vertical fiducial line (the red line in Figure 3) in the side telescope.

(3) Focus the side telescope on the left filament post. Note the image of the left filament is not so clear but you can still tell when the telescope is focused on the left post by adjusting the focus back and forward near the left filament post. Rotate the lamp about Z axis and adjust the lamp position along X axis so that the left post is also on the vertical fiducial line in the side telescope.

(4) Repeat steps 2 and 3 until both right and left filament posts are aligned onto the vertical fiducial line in the side telescope.

(5) Double check if all alignments are good by repeating steps 1, 2, 3 and 4.

(6) Focus the side telescope on the right side lamp filament (viewing the lamp from the photometer). Adjust the lamp position along X axis so that the distance reference point (the intersection point between the right side filament and the right lamp post) is aligned onto the vertical fiducial line (the distance origin) as shown in Figure 4.

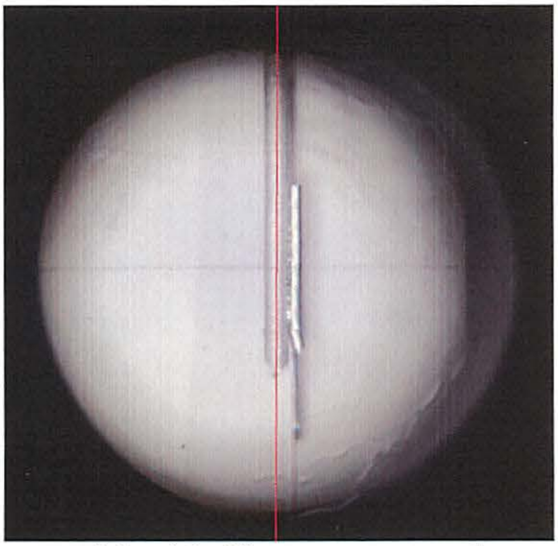


Figure 3 – Alignment of the right filament post onto the vertical fiducial line

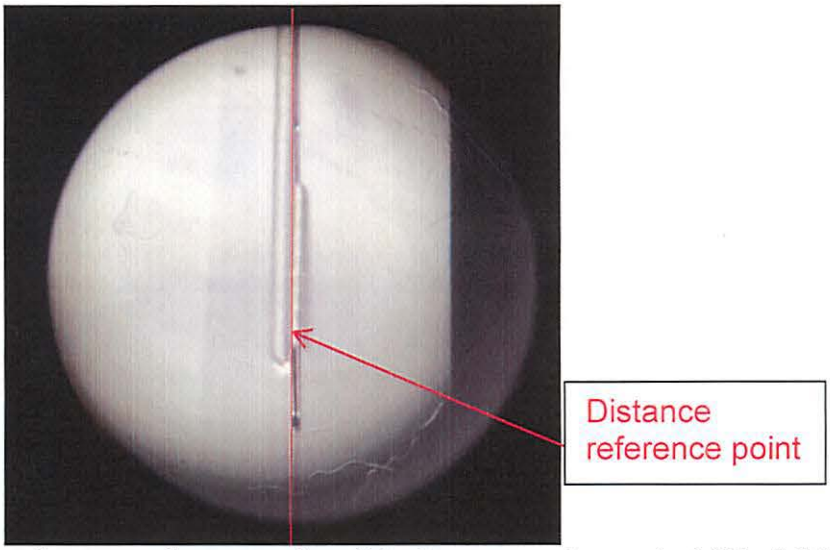


Figure 4 – Alignment of the distance reference point of the lamp onto the vertical fiducial line

The room temperature was 23 °C and relative humidity was approximately 47 % at the times of calibration. The equipment and the details of the calibration procedures of the luminous intensity and color temperature measurements are described in Section 3 and Section 7 of reference [1].

3. Results of the Calibration

The results of the before and after calibrations are shown in Table 1 and Table 2. The relative expanded uncertainty (with coverage factor k=2) of the luminous intensity value is 0.50 %, which includes the reproducibility of the test lamp. The uncertainty budget is shown in Table 3. The

REPORT OF CALIBRATION Manufacturer: Osram
Luminous Intensity and Color Temperature Calibration Model: Wi41/G
National Research Council of Canada Designation: NIST20100, NIST20101, NIST20102, NIST20103, NIST20104, and NIST20105

expanded uncertainty (k=2) of the color temperature value is 8 K as shown in Table 18 (page 60) of reference [1]. The NIST policy on uncertainty statements is described in reference [2].

Table 1. Results of Calibration for April 7th, 2014

Lamp No.	Current DC [A]	Voltage* DC [V]	Color Temperature [K]	Luminous Intensity [cd]	Std Dev [%]	Burning Time [min]
NIST20100	5.822	30.27	2855	283.0	0.10	90
NIST20101	5.918	30.60	2856	287.3	0.14	89
NIST20102	5.905	30.44	2855	288.5	0.08	91
NIST20103	5.877	30.51	2858	286.6	0.08	93
NIST20104	5.683	30.70	2858	272.7	0.08	91
NIST20105	5.922	30.59	2859	291.4	0.12	87

*Voltage is for reference only.

Table 2. Results of Calibration for August 14th, 2015

Lamp No.	Current DC [A]	Voltage* DC [V]	Color Temperature [K]	Luminous Intensity [cd]	Std Dev [%]	Burning Time [min]
NIST20100	5.822	30.26	2853	282.6	0.01	70
NIST20101	5.918	30.60	2855	287.5	0.12	67
NIST20102	5.905	30.43	2854	288.3	0.17	75
NIST20103	5.877	30.50	2856	285.9	0.09	65
NIST20104	5.683	30.70	2857	272.2	0.08	65
NIST20105	5.922	30.59	2857	290.8	0.06	64

*Voltage is for reference only.

4. General Information

The lamp should be carefully aligned in accordance with the procedures described above. The lamp should be operated on DC power at the reported current and at the prescribed polarity. Photometric measurements should be made at least 10 minutes after turning on. The uncertainty value is valid only for distances larger than 2 m.

Calibration Date: August 14, 2015
NIST Test No.: 2015CCPR-K3-F

REPORT OF CALIBRATION
Luminous Intensity and Color Temperature Calibration
National Research Council of Canada

Manufacturer: Osram
Model: Wi41/G
Designation: NIST20100, NIST20101, NIST20102, NIST20103, NIST20104, and NIST20105

The customer should take the uncertainty associated with the aging of the lamp and the calibration cycle into account.

The Calibration Report shall not be reproduced except in full, without the written approval of NIST.

Prepared by:

Yuqin Zong
Sensor Science Division
Physical Measurement Laboratory
(301) 975-2332

Reviewed by:

Maria Nadal
Sensor Science Division
Physical Measurement Laboratory
(301) 975-4632

Approved by:

C. Cameron Miller
For the Director,
National Institute of Standards and Technology
(301) 975-4713

References:

[1] Y. Ohno, NIST Special Publication 250-37 "Photometric Calibration" (1997)
[2] B. N. Taylor and C. E. Kuyatt, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," NIST Technical Note 1297 (1994).

Calibration Date: August 14, 2015
NIST Test No.: 2015CCPR-K3-F

REPORT OF CALIBRATION
Luminous Intensity and Color Temperature Calibration
National Research Council of Canada

Manufacturer: Osram
Model: Wi41/G
Designation: NIST20100, NIST20101, NIST20102, NIST20103, NIST20104, and NIST20105

Table 3. Uncertainty budget for this luminous intensity calibration

Uncertainty factor	Type	Relative standard uncertainty (%)
NIST illuminance unit realization	B	0.20
Long-term Drift of the NIST photometers	B	0.08
Photometer temperature variation	A	0.02
Distance measurement	B	0.01
Alignment of the lamp distance	A	0.10
Determination of *smcf**	B	0.02
Lamp current regulation and measurement	A	0.01
Stray Light	B	0.03
Random noise	A	0.05
Deviation from inverse square law	A	0.05
Combined uncertainty		**0.25**
Expanded uncertainty (*k*=2)		**0.50**

Calibration Date: August 14, 2015
NIST Test No.: 2015CCPR-K3-F

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Final Report

Appendix A

<u>NRC Report</u>

NRC Report

Six Osram Wi41/G lamps were used at the pilot (NRC) laboratory to represent the NRC luminous intensity scale for the comparison. These lamps are the six primary Osram Wi41/G lamps that were calibrated from room temperature absolute radiometers as described in our paper:
L.P. Boivin, A.A. Gaertner, and D.S. Gignac Realization of the New Candela (1979) at NRC, Metrologia **24**, 139-152 (1987).

As described in this paper, the NRC Candela was most recently realised in 1986, using room temperature electrical-substitution absolute radiometers to calibrate secondary radiometers. The absolute spectral responsivities of the secondary radiometers were measured at laser wavelengths 476.2 nm, 530.9 nm, 568.2 nm, 647.1 nm, and 676.4 nm. Auxiliary measurements using a monochromator apparatus were used to obtain calibration points below 476.2 nm, to 380 nm, and above 676.4 nm, to 800 nm. Interpolation techniques were used to obtain complete calibration data from 380 nm to 800 nm at 5 nm intervals. These secondary radiometers, which incorporated diffusers, were then used with V(λ)-correcting filters to calibrate the lamps. These photometers were not thermostated.
The equation for the luminous intensity of a lamp (I_v), as measured by the output voltage (V_{out}) of the photometer, is given by (see equation 1 of our above-mentioned paper):

$$I_V = \frac{683 \cdot V_{out} \cdot \left(d - {}^{t}/_{3}\right)^2}{R_f \cdot A} \cdot \frac{\int V(\lambda) \cdot I_e(\lambda) \cdot d\lambda}{\int S(\lambda) \cdot T(\lambda) \cdot I_e(\lambda) \cdot d\lambda}$$

where

- R_f = feedback resistance of the detector amplifier,
- A = area of the radiometer aperture,
- D = distance between the lamp filament and the radiometer aperture,
- t = thickness of the V(λ)-correcting filter,
- $I_e(\lambda)$ = relative spectral distribution of the lamp,
- $S(\lambda)$ = absolute spectral responsivity of the secondary radiometer, and
- $T(\lambda)$ = spectral transmittance of the filter.

The lamps are OSRAM type Wi41/G, operating at a colour temperature of 2800 K. The colour temperature of these luminous intensity lamps was set to 2800K when they were first calibrated in 1987.
These lamps have been used very little since that time, so the luminous intensity values assigned to these lamps is the same as at their calibration in 1986. These six lamps are also used as the primary standards to maintain the candela at NRC. An estimate of the aging of the lamps due to use since they were calibrated is included in the uncertainty budget as indicated below.

The lamp specifications are given below:

NRC Luminous Intensity Standards			
Lamp	**SET current (amperes)**	**Voltage (volts)**	**Luminous Intensity (candela)**
021	5.6610	30.356	254.4
022	5.6195	30.069	251.6
023	5.6346	30.211	254.0
026	5.6499	30.398	252.2
027	5.6654	30.461	254.6
030	5.6329	30.106	253.8

The statement of the uncertainty in the calibration of these lamps is given in Table 2 of our above-mentioned paper, and reproduced below.

NRC Uncertainty Budget		
Source of Uncertainty	**Type**	**Relative Standard Uncertainty (k=1)**
Systematic (Type B) effects*		
Calibration of secondary radiometer:		
-calibration uncertainty:	B	0.15%
-non-uniformity:	B	0.25%
-aperture area:	B	0.10%
temperature variation:	B	0.08%
Filter effects:		
-transmittance:	B	0.20%
-wavelength shift:	B	0.20%
-temperature variation:	B	0.20%
Measurement repeatability:	B	0.15%
Electrical Effects:	B	0.10%
Imperfect V(λ):	B	0.15%
Lamp Maintenance / aging[1]	B	0.30%
Total Type B uncertainty (SumSq):		0.61%
Random (Type A) effects		
Lamp reproducibility[2]	A	0.10%

Total (Type A+B) uncertainty (SumSq):		**0.61%**
*L.P.Boivin, A.A.Gaertner, and D.S.Gignac, **Realization of the New Candela (1979) at NRC** -Metrologia **24**, 139-152 (1987)		

1. The term ‘Lamp Maintenance/aging’ is added to the original uncertainties as an estimate of the uncertainty in the luminous intensity values of the lamps used for the comparison since the time that they were calibrated. This is predominantly an estimate of the aging of the lamps due to use since they were calibrated.
2. The lamp alignment component is included in the lamp reproducibility term.

CCPR Key Comparison CCPR-K3.2014

Luminous Intensity

Draft B Report

Appendix B

Review of Uncertainty Budgets

- replies to general comments

- replies to questions to specific NMIs

- attachments:

- VNIIOFI, NPL, NMIJ, NMISA

1. We would like to clarify whether reflections off the inside edges of baffles or shutters have been included, either as corrections (with associated components in the uncertainty budget) or as uncertainty contributions. The most common geometry (circular opening) for baffles results in ray paths from the source, reflecting off the inside edge of the baffle back towards the detector. We believe that, even though the baffle material may only be a fraction of a millimetre thick, these ray paths can cause appreciable reflection of light into the detector which should not be included in the measurements. This is exacerbated by the grazing incidence geometry of these ray paths. We think that shutters used in determining the background level are likely to interrupt these ray paths so the effect is not eliminated by background subtraction. Rectangular openings suffer from the same issue, although to a reduced extent. We have observed contributions up to 0.08% per baffle, strongly dependent on the baffle geometry. A brief reference to this effect, although in a different context, has been made in the literature (Metrologia , 621 (2000)).

: Straylight created by baffles in the light path depends strongly on their shapes and the construction of the edges and it is not corrected by background subtraction. This yields similarly for straylight back reflected from the light trap behind the lamp. The effect of this type of straylight is mostly compensated if luminous intensity lamps are used as reference standards for the transfer standards within the CCPR comparison as performed by the PTB. Provided this type of straylight contributes significantly to the combined uncertainty then it has to be mentioned in the model of evaluation and in the uncertainty budget. It should be mentioned that the baffles used at the PTB create a relative straylight $<5\cdot10^{-5}$. In case the photometer is reference for the calibration of the luminous intensity standard lamps the uncertainty of the aperture has to be taken into account and only then the given reference [Metrologia , 621 (2000)] is helpful.

: The reflections of baffles or shutters edge is a part of stray light, we estimated the stray light and made a correction to the measured photocurrent of lamp. The uncertainty budget of stray light is the imperfection of stray light correction.

: The lamps used for the comparison were calibrated directly against NPL's primary reference standard luminous intensity lamps, which are of exactly the same type as the comparison lamps. Any reflections from the inside edges of baffles or shutters are therefore common to both the reference and comparison lamps and the effects cancel; no correction is necessary. Extensive investigations into stray light effects (including light scattered, reflected or diffracted by apertures and baffles) were carried out during the realisation of the luminous intensity scale and assessed to be less than 0.01 % - this is included in the uncertainty budget for NPL's realisation of the candela.

: Following the first General Comment of the pre-Draft A Process 2, we recently tried to estimate an uncertainty associated with scattering in inner edges of baffles, but suddenly realized that our measurements (both rounds) were mistakenly done without a thin edge aperture on a shutter. So, the thickness of the actual edge was too thick and gave quite strong reflectance. We have measured this effect and found that the luminous intensity values have to be reduced. Please find the corrected files attached. (See attached pages VNIIOFI response for the revised Appendix A.5 uncertainty budget.) Corrected values are marked red. All luminous intensity values are reduced. The uncertainty component associated with stray light is increased from 0.02% to 0.1%; the total uncertainty is increased up to 0.25% and 0.26% for the 1st and 2nd rounds, respectively.

: There are two irises (used as baffles) and one electric shutter between the lamp and the photometer. The first and second irises are located at approximately 0.6 m and 1.85 m, respectively from the lamp. The thickness of the iris blades is 0.2 mm. The photometer is at 3.5 m away from the lamp. The measurement uncertainty resulting from the reflected light is analyzed using the optical ray tracing technique. The shutter does not cause any reflected light because its opening is larger enough so that it is completely hidden behind the second iris (i.e., it is in the dark). The first iris does not contribute to the measurement error because the angle of its reflected light is large enough so that the reflected light cannot reach the photometer. The uncertainty resulting from the reflected light from the second iris is estimated to be less than 0.01 % and therefore no correction is applied. Instead it is rolled into our 0.05% stray light uncertainty component, which also includes the scatter light from the edge of iris, the inter-reflection between the photometer, photometer mount, irises, wall of the photometry bench, and light trap, etc.

2. Comment for all the laboratories that are using an aperture:
If the aperture plane is not perpendicular to the optical axis, the effective aperture area will be smaller than that at the normal position. This uncertainty component is not in the uncertainty list. (NMIA, LNE-CNAM, VNIIOFI, NRC).

: Usually the photometer´s aperture plane is aligned by help of a mirror and a back reflected laser beam and any deviation from the perpendicular direction has to be weighted by the cosine. The effect of this misalignment is mostly compensated if the mounting of the photometer was unchanged between its calibration as reference and the transfer to the transfer standards within the CCPR comparison. Provided this misalignment contributes significantly to the combined uncertainty then it has to be mentioned in the model of evaluation and in the uncertainty budget.

: The alignment of the NPL photometer was not changed between the calibration using the reference lamps and the measurements of the comparison lamps; therefore it is not necessary to include an uncertainty component for misalignment of the photometer aperture.

:This uncertainty component (tilt) is included in the derivation of the uncertainty in the aperture area, although those details were not included in our uncertainty budget. However, it is true that a component due to this effect when using the aperture has not been included. Using a retro-reflected laser, we have estimated the possible tilt in the aperture when it is mounted in our usual way. The tilt is estimated to be approximately 0.08 degrees, so the contribution to the uncertainty is negligible. For consistency with our comments below, we could submit a revised budget with this term included (and set to zero) if participants considered it would add value.

: This uncertainty is included in the 'Measurement repeatability' component.

: Using a mirror and retro laser along with mechanical alignment the aperture alignment off axis is very small. Less than 0.002% as captured in Table 5 of "Yuqin Zong, Maria E. Nadal, Benjamin K. Tsai, and C. Cameron Miller, "Photometric Calibrations," NIST Special Publication 250-95. (2018). https://doi.org/10.6028/NIST.SP.250-95 "

3. It turns out that the variety of measurement budgets, and the components mentioned in there, is quite large. However, when I received the document to review the uncertainty budgets, I was really surprised that obviously only very few (3 of 11) participants have sent their model for evaluation which they used to establish their distinct associated uncertainty budget.
According to GUM, the uncertainty budget of a measurement must be based on a measurement model which clearly connects input and output parameters by means of a physical equation to show the interdependencies and the sensitivities of the various uncertainty contributions.
It would have been nice, if every participant would have used the uncertainty determination according to the Technical Report CIE 198:2011, where a clear GUM compliant example for the determination of the uncertainty of luminous intensity is given, but only IO-CSIC, METAS and PTB followed that route.
At least for me, it is not possible to judge about the legitimacy of a stated uncertainty contribution of the other participants, where no information about the model of evaluation and the measurement process is given.

If we take the first of the eleven budgets as an example:

NMISA simply copied your example of the measurement uncertainty from the Technical Protocol – which I supposed to be only an example to show the difference between what you call "Systematic" and "Random" effects. (BTW, I was not in favour of this chart because it is not strictly according to GUM). In case of NMISA the selection of possible uncertainty components from the (already) condensed Technical-Protocol-example might be good for a rough uncertainty estimation, but not for a meaningful demonstration of metrology at the high level of a CCPR comparison. May be that, e.g., stray-light is the most important environmental issue at NMISA but at least spectral mismatch of used photometer is always an issue and may not be neglected. May be that this contribution is hidden elsewhere, but without further information such a kind of uncertainty budget without model of evaluation is not sufficient. It is simply not possible to judge about the correctness of the stated uncertainties – and this is valid for all those participants showing only condensed budgets without models of evaluation.

Moreover, also the differentiation between "random" and "systematic" effects seems not to be generally understood in the same way. Different participants subsume different type of components under these classifications.
Therefore, at the current stage, and without further information, I can only agree with the uncertainty budgets from IO-CSIC, METAS and PTB.

: In the Technical Protocol for this CCPR comparison chapter 6.1.1 the GUM is explicitly claimed as reference for any statement of measurement uncertainty. Additionally, the chapter 6.1.2 refers to the document CIE 198 as example for modeling combination and presentation. The protocol itself gives in Appendix A.5 an example for an abbreviated presentation. Thus, the model of evaluation is an essential part in the documentation and has to be stated individually by each participant as well as the complete uncertainty budget from CIE 198 as an intermediate step for the summarized presentation recommended in Appendix A.5 to simplify the comparison of individual contributions.

: The uncertainty assessment should be carried out in accordance with GUM, as mentioned in 6.1.1 of the technical protocol of CCPR-K3.2014. Although CIE 198:2011 give us a good example of uncertainty assessment for luminous intensity, other approaches in accordance with GUM should also be accepted.
Our uncertainty assessment is consistent with GUM. The protocol didn't require submission of mathematical models and analysis procedure. We only submit the uncertainty budget table which condenses the procedure of uncertainty assessment. Some insignificant uncertainty components are not listed, such as temperature effect, etc.

: See attached pages (NPL response) for NPL answers.

: See attached pages (NMIJ response) for NMIJ answers.

:One of the more valuable aspects of comparisons is the diversity of uncertainty budgets, allowing a full range of components to be identified by the metrology community. If all participants were to use an identical methodology for constructing their budgets, the possibility of identifying effects that should be included would be reduced. We therefore believe that uniform use of CIE 198 would be a backward step.

The logic that we used in distinguishing between random and systematic components followed the requirements of the protocol. It described systematic components as producing their unknown values from one measurement to the next, adding that they will probably be the same for a complete round of measurement. Given that measurements on the comparison artefacts were performed by transfer from a set of working standard lamps over a short period of time using a common set of instrumentation, the majority of effects are labelled as systematic. The random components are those associated with the complete realignment of the comparison lamps between measurements, lamp reproducibility and noise.

: See Sections 1 and 3 of "Yuqin Zong, Maria E. Nadal, Benjamin K. Tsai, and C. Cameron Miller, "Photometric Calibrations," NIST Special Publication 250-95. (2018). https://doi.org/10.6028/NIST.SP.250-95 "

:

Model of evaluation:

See attached page (NMISA response) for NMISA Uncertainty Budget Matrix (UBM).

$$I = \frac{K_m d^2 F I_c}{SA}$$

where

I is the luminous intensity

K_m is the luminous efficacy

D is the distance from the lamp filament to the photometer

F is the spectral mismatch factor

I_c is the current, determined for the gain of the amplifier and the voltage as measured for the LMT photometer

S is the responsivity of the LMT photometer

A is the area of the LMT photometer

- Spectral mismatch: We corrected for spectral mismatch and therefore did not include it in the model of evaluation.
- Lamp alignment: We allowed for 1° uncertainty in the alignment of the lamps, as you can see in the model of evaluation.

The lamp alignment uncertainty seems quite large, although it is listed as Type A uncertainty. Is there a specific effect that produces this large uncertainty?
We allowed for 1° uncertainty in the alignment of the lamps, as you can see in the model of evaluation.

The NMIA budget seems too complicated. It’s a bit hard to understand it without the facility and measurement procedure description. I hope this description will appear in the Draft A report.
We have attempted a comprehensive evaluation of all the effects that could influence our measurements, and their associated uncertainties. Quite a few of them have been evaluated as zero (to the number of significant digits in our budget) but we considered it worthwhile to leave them in the budget since they had been considered. It is true that the budget could also have been simplified by replacing groups of related components with single combined values, but we believe that it was better to provide a detailed breakdown.
We acknowledge that a description of the measurement facility and process is an important part of assessing the budget. We have written our report and will be very happy to modify or extend it as required to provide the information requested by other participants during the relevant part of the report preparation.

The random effects section includes a lamp ageing component which is quite large and dominates this part of the budget. Could you explain what this means?
See attached pages (NMIJ response) for NMIJ answers.

It is not stated which components are considered as random and which are systematic in the context of the Appendix A6 table. Could, for example, an extra column be added to the Appendix A5 table giving that classification?
IO-CSIC has submitted a revised Appendix A.5 in which an extra column has been added. From column 3 of the original table, all Type A (2) have been labelled as Random and all Type B have been labelled as Systematic. See Appendix A of this comparison report.

The lamp alignment uncertainty seems quite large, although it is listed as Type A uncertainty. Is there a specific effect that produces this large uncertainty?

It is not stated which components are considered as random and which are systematic in the context of the Appendix A6 table. Could the components numbers in the Appendix A5 table be listed as random or systematic (or is that what the asterisks in that table indicate)?
The answer is yes, the * indicates the random effects.

1. Is it possible that the 'stabiliser current control' contributes to the 'test lamp repeatability' component, meaning that there is some double counting in the random effects?
   Yes, it is impossible to isolate the effect of 'stabiliser current control' from 'test lamp repeatability' so there is potentially a small element of double counting in the random effects. However since the test lamp repeatability component is intended primarily to allow for lamp alignment variations and is treated as a worst case estimate, we have chosen to ignore this small element of double counting. The effect on the final uncertainty is insignificant.
2. If they know the ageing rate of the lamp, it is better to correct the luminous intensity according to the ageing rate. If they do the correction, the uncertainty will be smaller than 0.125%.
   We do not know the actual change in luminous intensity due to ageing for each individual reference lamp used. Each reference lamp has been used for a different length of time since the original calibration and will also age at a slightly different (unknown) rate. We therefore do not correct for ageing effects. The uncertainty estimate is a conservative allowance, which is based on measurements on other lamps of the same type operated at the same correlated colour temperature and under the same conditions coupled with knowledge of the maximum length of time for which the reference lamps have been used since the original calibration.
3. Some expressions are not consistent with the requirements of GUM "Evaluation of measurement data-Guide to the expression of uncertainty in measurement", such as "value ±", "ui", "Photocurrent measurement accuracy".
   - "ui"should be "u_i"
   - "Photocurrent measurement accuracy" should be "Photocurrent measurement"

   We apologise for these typing mistakes, which were due to importing the table from an Excel file. We have provided a corrected version of the report to the pilot laboratory.
4. The uncertainty of lamp alignment is not in the list.
   The uncertainty due to lamp alignment is included under 'Test lamp repeatability' as described in section 5.10 of our report.

Please clarify the two lines labelled "variance" at the end of the Appendix A5 table. Do they indicate the distinction between the random and systematic uncertainties in the context of the comparison? Similarly, could the components in the Appendix A5 table be labelled somehow (or a separate list be given) as contributing to the random and systematic uncertainties?

a) According to the GUM all entries in Appendix A.5 are labeled in column 6 with "A" for "statistical" or "B" for any "other determination". These types of entries are combined and listed separately for each lamp. The list was send to the pilot for an additional explanation and mean values $u(\text{A})$ = 0.12% and $u(\text{B})$ = 0.13% are indicated. Thus, the combined standard uncertainty for the transfer by only one lamp is $u(I) = \sqrt{u(\text{A})^2 + u(\text{B})^2}$ = 0.18%.

b) At the bottom of the table Appendix A.5 two values labeled u_{dev} = 0.12% for random ("dev" for devise) and u_{inst} = 0.14% for systematic contributions ("inst" for instrumentation) are included. These numbers, their meaning and the evaluation are explained in all details in the publication CIE 198-SP1.2:2011 (see chapter/example 2.13).

The combination of these numbers to determine the uncertainty of the whole batch for the transferred value of intensity is explained in great detail in CIE 198-SP1.1:2011 example 1.11.

It turns out that the instrumentation for the two rounds at PTB was stable and the properties of the PTB-transfer-standards (WI41/G) are uniform. A separation in types A and B or "random" and "systematic" gives no real difference. So, the uncertainty *u*(PTB) associated with the luminous intensity value transferred by with a number of 6 PTB-transfer standards will be determined by the pilot laboratory from

$$u(I)_{\mathrm{PTB}} = \sqrt{u_{inst}^2 + \frac{u_{dev}^2}{6}} = 0.15\%.$$

The values for the systematic component given in the second table (±0.20%) appear to derive only from the illuminance unit realisation. Should the long-term drift of the photometers be included in the systematic component?

As shown in Table 8 of "Yuqin Zong, Maria E. Nadal, Benjamin K. Tsai, and C. Cameron Miller, "Photometric Calibrations," NIST Special Publication 250-95. (2018). https://doi.org/10.6028/NIST.SP.250-95", we do have a longterm drift component but these measurements were done within 1 month of the scale realization so there is no longterm drift.

There is no lamp alignment component – is it included in the lamp reproducibility term? Please also clarify the meaning of the term labelled as "Lamp Maintenance / aging".

The lamp alignment component is included in the lamp reproducibility term.

The term 'Lamp Maintenance/aging' is an estimate of the uncertainty in the luminous intensity values of the lamps used for the comparison since the time that they were calibrated. This is predominantly an estimate of the aging of the lamps due to use since they were calibrated.

Appendix A.5 Sample Measurement Uncertainty Budget **(VNIIOFI response)**

Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
Systematic effects:		
Calibration of working standards		
- Photometers of LMT P150T type	B	0.19
Electrical		
- standard resistor	B	0.002
- voltmeter	B	0.07
Photometer		
- spectral mismatch	B	0.001
- linearity	B	0.01
- distance	B	0.05
Environment		
- stray light	B	**0.1**
- temperature / humidity	B	0.02
Lamp alignment (systematic component)	B	0.03
Discrepancy between photometers (systematic)	B	0.04
Stability of photometers*	B	0.07
RMS total systematic effects:		
1st Round		**0.24**
2st Round		**0.25**
Random effects:**		
Electrical parameters:		
- power supply fluctuations, u_{psf}	B	0.02
Photometer noise (25 readings), u_{noise}	A	0.001
Discrepancy between three photometers (random), u_{pd}	A	0.05
Independent measurement reproducibility *** , u_{rep}	A	0.05
RMS total random effects****:		**0.06**
RMS total standard uncertainty:		
1st Round		**0.25**
2st Round		**0.26**

* For the second round only
** Standard deviations varied from set to set and from lamp to lamp. Typical values are presented in the table.
*** Each independent measurement was done with total re-alignment of a lamp and the photometers. Random effect associated with independent measurement reproducibility comprises several random effects: lamp alignment, photometer alignment, random error in distance measurement, lamp fluctuation.

**** Uncertainty associated with reproducibility (u_{rep}) partly includes uncertainties associated with other random effects. Therefore, the Total random uncertainty is calculated as

$$u_{Total,Random} = \sqrt{u_{\text{rep}}^2 + (u_{\text{pd}}^2 + u_{\text{noise}}^2 + u_{\text{psf}}^2)/n}$$

where $n = 4$ – the typical number of independent measurements

Measurement parameters given in this table are suggested. Please modify and itemize according to your particular situation. See Section 6.2 for explanation of the various items.

Note that if lamps are used as the laboratory working standards, a group of uncertainties would need to be included in the above table to account for their behaviour.

The RMS total refers to the usual square root of the sum of the squares of all the individual uncertainty terms.

Contact person: Boris Khlevnoy

NMI: VNIIOFI

Date: 25 November 2015

Signature:

NPL response to questions relating to uncertainty budgets for CCPR-K3.2014

General comments / questions

1. The lamps used for the comparison were calibrated directly against NPL's primary reference standard luminous intensity lamps, which are of exactly the same type as the comparison lamps. Any reflections from the inside edges of baffles or shutters are therefore common to both the reference and comparison lamps and the effects cancel; no correction is necessary. Extensive investigations into stray light effects (including light scattered, reflected or diffracted by apertures and baffles) were carried out during the realisation of the luminous intensity scale and assessed to be less than 0.01 % - this is included in the uncertainty budget for NPL's realisation of the candela.

2. The alignment of the NPL photometer was not changed between the calibration using the reference lamps and the measurements of the comparison lamps; therefore it is not necessary to include an uncertainty component for misalignment of the photometer aperture.

3. NPL did not follow the model given in CIE 198:2011 since this is not how we usually structure our uncertainty budget. We did, however, provide a detailed description of each of the uncertainty contributions included in our uncertainty budget, which we believe gives the information necessary to judge the legitimacy of each of these. For completeness, our measurement equation is given below (this has also been added to our measurement report):

$$I_{\mathrm{v},t} = C_{\mathrm{cal}} V_t (1 + C_{\mathrm{d},t})(1 + C_{\mathrm{J},t})(1 + C_{\mathrm{p},t}) F_{\mathrm{SM},t} (1 - C_{\mathrm{stray},t})(1 + C_{\mathrm{align},t}) \qquad (1)$$

   where

$$C_{\mathrm{cal}} = \frac{(I_{\mathrm{v},r} + C_{\mathrm{age},r})}{V_r} \qquad (2)$$

   and

   $I_{\mathrm{v},t}$ is the luminous intensity of test (comparison) lamp *t*

   C_{cal} is the mean photometer calibration factor, calculated using Equation 2 and averaged across all the reference lamps used

   $I_{\mathrm{v},r}$ is the luminous intensity of reference lamp *r*

   $C_{\mathrm{age},r}$ is the change in luminous intensity of reference lamp *r* since its original calibration due to ageing

   V_r is the mean reading from the photometer for reference lamp *r*

   V_t is the mean reading from the photometer for test lamp *t*

   $C_{\mathrm{d},t}$ is the error in luminous intensity for test lamp *t* due to error in setting the filaments of the reference and test lamps in the same vertical plane

   $C_{\mathrm{J},t}$ is the error in luminous intensity for test lamp *t* due to error in setting the current for the test lamp to the specified value (the uncertainty due to error in setting the current for the reference lamp to the specified value is included in the uncertainty budget for the luminous intensity of the reference lamp)

$C_{\mathrm{p},t}$ is the error in luminous intensity for test lamp t due to differences in amplifier gain and DVM sensitivity between measurement of the photocurrent produced by the reference lamp and that produced by the test lamp

$F_{\mathrm{SM},t}$ is the spectral mismatch correction factor for test lamp t

$C_{\mathrm{stray},t}$ is the error in luminous intensity for test lamp t due to differences in stray light between the reference and test lamps

$C_{\mathrm{align},t}$ is the error in luminous intensity for test lamp t due to misalignment of the lamp (the uncertainty due to misalignment of the reference lamp is included in the uncertainty budget for the luminous intensity of the reference lamp)

Note all of the *C* terms listed above have an expected value of zero and an associated uncertainty that has been estimated as described in our measurement report.

Specific comments / questions

1. Yes, it is impossible to isolate the effect of 'stabiliser current control' from 'test lamp repeatability' so there is potentially a small element of double counting in the random effects. However since the test lamp repeatability component is intended primarily to allow for lamp alignment variations and is treated as a worst case estimate, we have chosen to ignore this small element of double counting. The effect on the final uncertainty is insignificant.

2. We do not know the actual change in luminous intensity due to ageing for each individual reference lamp used. Each reference lamp has been used for a different length of time since the original calibration and will also age at a slightly different (unknown) rate. We therefore do not correct for ageing effects. The uncertainty estimate is a conservative allowance, which is based on measurements on other lamps of the same type operated at the same correlated colour temperature and under the same conditions coupled with knowledge of the maximum length of time for which the reference lamps have been used since the original calibration.

3. We apologise for these typing mistakes, which were due to importing the table from an Excel file. We have provided a corrected version of the report to the pilot laboratory.

4. The uncertainty due to lamp alignment is included under 'Test lamp repeatability' as described in section 5.10 of our report.

Dear Dr. Gaertner,

The following equations are the physical model of uncertainty of luminous intensity at NMIJ.

$$I_1 = \frac{K_m (d_1 + \Delta d_1)^2}{A} \frac{V_0}{G} \frac{\int_{\lambda_1}^{\lambda_2} \Phi_{e,\lambda}(\lambda)\ V(\lambda)\ d\lambda}{\int_{\lambda_1}^{\lambda_2} \Phi_{e,\lambda}(\lambda)\ s_e(\lambda)\ d\lambda} (1 + c_t)\ (1 + c_1) \quad (1)$$

$$I_2 = I_1\ k_c \frac{V_2}{V_1} \frac{(d_2 + \Delta d_2)^2}{{d_2}^2} (1 + c_i)\ (1 + c_a)\ (1 + c_2)\ (1 + c_3) \quad (2)$$

Equation (1) is the model to determine the luminous intensity of the standard lamp. Equation (2) is the model to transfer luminous intensity from the standard lamp to the transfer lamp. The meanings of each variable are listed below.

I_1 : Luminous intensity of a standard lamp.

K_m : Maximum luminous efficiency constant. No uncertainty.

d_1 : Distance between the standard lamp and the standard photometer. Constant. No uncertainty.

Δd_1 : Deviation of distance setting.

A : Aperture area of the standard photometer.

V_0 : Voltage measured by the multimeter. Uncertainty negligible.

G : Conversion ratio of the current-voltage converter. Uncertainty negligible.

$\Phi_{e,\lambda}(\lambda)$: Relative spectral distribution of the standard lamp. Uncertainty to luminous intensity negligible.

$V(\lambda)$: Luminous efficiency function. No uncertainty.

$s_e(\lambda)$: Spectral responsivity of the standard photometer. Uncertainty of this factor consists of two parts in the budget. One is "Spectral responsivity of the silicon photodiode measured with the cryogenic radiometer", and another is " Illuminance responsivity of the standard photometer with respect to the spectral responsivity of the silicon photodiode".

c_t : Deviation of the standard photometer responsivity by the room temperature.

c_1 : Deviation of the luminous intensity measurement for the standard lamp set on and removed from the lamp mount in many times. Accumulated data.

I_2 : Luminous intensity of the transfer lamp.

k_c : Colour correction factor between the standard lamp and the transfer lamp. Uncertainty negligible.

V_2 : Voltage output measured for the transfer lamp.

V_1 : Voltage output measured for the standard lamp.

d_2 : Distance between the lamp and the comparison photometer.

Δd_2 : Deviation of distance setting.

c_i : Effect of the lamp current uncertainty.

c_a : Deviation of luminous intensity through the period of recalibraion-limit burning time. We take this effect into the uncertainty without correction. So it is listed in "Random effects" because we cannot predict what value a lamp will take at each burning.

c_2 : Deviation of the luminous intensity measurement for the transfer lamp set on and removed from the lamp mount in many times. Accumulated data.

c_3 : Fluctuation of lamp signal.

The variables correspond to the uncertainty budget as follows.

	Measurement Parameter	Uncertainty Type (A or B)	Standard Uncertainty in luminous intensity (%)
	Systematic effects:		
	Calibration of working standards		
$s_e(\lambda)$	- Spectral responsivity of the silicon photodiode measured with the cryogenic radiometer	B	0.05
$s_e(\lambda)$	- Illuminance responsivity of the standard photometer with respect to the spectral responsivity of the silicon photodiode	B	0.20
Δd_1	- Measurement of the distance between the primary standard lamp and the transfer detector	B	0.05
c_t	- Responsivity change of the transfer detector by room temperature fluctuation	B	0.10
c_1	- Setting of the luminous intensity primary standard lamp	B	0.10
A	- Aperture area	B	0.015
	Electrical		
	- standard resistor		negligible
c_i	-digital multimeter	B	0.01
	Photometer		
	- spectral mismatch		negligible
	- linearity		negligible
Δd_2	- distance	B	0.02
	Environment		
	- stray light		negligible
	- temperature / humidity ?		included in (*)
	RMS total systematic effects:		0.256

NMIJ response Page 2 of 3

	Random effects:		
	Lamp parameters:		
c_a	- lamp ageing	B	0.11
c_2	- lamp alignment (*)	B	0.06
	- lamp reproducibility		included in (*)
c_3	- lamp output fluctuations	B	0.02
	Electrical parameters:		
	- power supply fluctuations		included in (*)
	Photometer noise		included in (*)
	(Measurement Set standard deviation of mean)		
	RMS total random effects:		0.127
	RMS total standard uncertainty:		0.29

The effect of baffles is regarded as negligibly small. We expect that that effect can be as small as 0.007 %, which is negligible in the NMIJ's uncertainty budget.

NMISA response, page 1 of 1	UNCERTAINTY BUDGET MATRIX (UBM)	Certificate No	
		Procedure No	

Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9)

Description:	CCPR-K3 Luminous Intensity Intercomparison	Type & Serial Number		Range:		Metrologist

Mathematical Model:

Symbol	Input Quantity (Source of Uncertainty) (X_i)	Estimated Input Quantity (x_i)	Estimated Uncertainty	Unit	Probability Distribution (N, R, T, U)	k= ▼	Divisor factor	Standard Uncertainty $U(Xi)$	Sensitivity Coefficient Ci	Unit	Standard Uncertainty Contribution $Ui(y)$	Reliability %	Degrees of Freedom v	Remarks
▼ Standards and Reference Equipment (Uncorrelated) ▼											Unit			
Std	Photometer (LMT)		1.300000	%	Normal k = 2		2.00	6.500E-01	1.000E+00		6.500E-01	100.00	infinite	From certificate OR\SR-5082
	Spatial uniformity		0.100000	%	Rectangular √3		1.73	5.774E-02	1.000E+00		5.774E-02	95.00	200.00	Literature Type B
	Distance uncertainty		0.018170	%	Normal k = 2		2.00	9.085E-03	1.000E+00		9.085E-03	100.00	infinite	Optical bench certificate DM\DIM-4016 type B
	Lamp fluctuations during operation (lamp stability		0.003100	%	Normal k = 1		1.00	3.100E-03	1.000E+00		3.100E-03	100.00	infinite	Empirical test Type A, I:\Laboratories\Optical Radiomet
	Lamp alignment		1.000000	deg	Rectangular √3		1.73	5.774E-01	2.467E-01	%/deg	1.424E-01	100.00	infinite	Empirical test PH-03, sens coef unit is %/deg type A
	Electrical noise on photometer signal		0.000100	%	Normal k = 1		1.00	1.000E-04	1.000E+00		1.000E-04	100.00	infinite	Empirical test Type A, I:\Laboratories\Optical Radiomet
	Lamp power setting (lamp current)		0.000450	%	Normal k = 1		1.00	4.500E-04	1.000E+00		4.500E-04	100.00	infinite	Empirical test Type A, I:\Laboratories\Optical Radiometr
	Drift/ageing of lamps		0.063100	%	Normal k = 1		1.00	6.310E-02	1.000E+00		6.310E-02	100.00	infinite	Type A I:\Laboratories\Optical Radiometry\Irma\Intercor
	electrical - std resistor		0.007410	%	Normal k = 2		2.00	3.705E-03	1.000E+00		3.705E-03	100.00	infinite	Certificates, type B, I:\Laboratories\Optical Radiometry\
	electrical - voltmeters		0.001760	%	Normal k = 2		2.00	8.800E-04	1.000E+00		8.800E-04	100.00	infinite	Certificates, type B, I:\Laboratories\Optical Radiometry\
	Stray light		0.030000	%	Normal k = 1		1.00	3.000E-02	1.000E+00		3.000E-02	100.00	infinite	Empirical test Type A, I:\Laboratories\Optical Radiomet
Res	Resolution of Standard / Equipment (If applicable)											100		
▼ Standards and Reference Equipment (Correlated) ▼								NOTE!	ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED					
▼ Unit Under Test / Calibration (Uncorrelated) ▼								NOTE!	ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED					
Res	Resolution of UUT (If applicable)											100		
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		0.003	%	Normal K = 1		1.00	3.300E-03	1.000E+00		3.300E-03		4	No of Readings 5
▼ Unit Under Test / Calibration (Correlated) ▼								NOTE!	ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED					

About UBM	TOTAL COMBINED UNCERTAINTY		Unit			
Best Measurement Capability (<u>Excluding</u> UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	6.716E-01	V_{eff}	3662867	Checked and Approved By:
	Expanded Uncertainty	**68,27 % K = 1**	**6.72E-01**	**k =**	**1.00**	
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	6.716E-01	V_{eff}	infinite	
	Expanded Uncertainty	**68,27 % K = 1**	**6.72E-01**	**k =**	**1.00**	

CCPR-K3.2014: Luminous Intensity
Draft B Report
2020-October-15
Information for Appendices C-F
Summary of Measurement Data and Analysis

(k=1) values are used for all calculations

Appendix C
Summary of Participant Lamp Luminous Intensity Values

This worksheet contains the Luminous Intensity values for all the participant lamps
The values for Round#1, Round#2, and the final values have been determined as discussed in the Draft B report Section 4.2 "Participant Lamp Data"
The worksheet shows the calculations for the average NMI Luminous Intensity relative standard uncertainty
The lamp final data is linked to subsequent worksheets and calculations

Appendix D
Summary of Pilot Measurements of Participant Lamps

This worksheet combines the 'final' NMI luminous intensity values (from Appendix C) with the Pilot measurements of each lamp
The final NMI value for the comparison photometer responsivity (cd/V) is calculated from all the NMI lamps and Pilot measurements
Uncertainties are calculated as discussed in the Draft B report Sections 4.1 to 4.3

Appendix E
Calculation of the KCRV and the DoE

The data from worksheet Appendices C and D is gathered for the calculation of the KCRV and Unilateral DOE
The calculations are discussed in the Draft B report Section 4.4
If any changes are made, such as to the Mandel-Paule factor s,
-the Chi-square values, KCRV value, DOE values and uncertainties will all change.

Worksheet "DOE.plt"

Plot of the DOE values, uncertainties, and KCRV uncertainty, data from Appendix E
This is similar to Figure Two of the Draft B report

Appendix F
Calculation of the Bilateral DoE

The data from Appendix E is used to calculate the bilateral DOE as described in the Draft B report Section 4.4.3

Appendix_Cv2.1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	**CCPR-K3.2014: Luminous Intensity**														**Fractional Split of NMI**		
2	**Draft B Report**														**random uncertainties**		
3	**2020-October-15**														**into uncorrelated and**		
4	**Appendix Cv2.1**														**correlated components**		
5	**Summary of Participant Lamp Luminous Intensity Values**														**for combining lamps**		
6															**fraction f**	**SQRT(1-f^2)**	
7															**0.5**	**0.866**	
8																	
9																	
10	NMI:	**NMISA**															
11																	
12	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**NMISA Lamp Luminous Intensity (cd)**					**Calculations for NMISA weighted mean**					
13				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
14								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
15								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
16																	
17	“24” 4595 PTB 09	R#1	“24” 4595 PTB 09R#1	5.824	30.242	2841.0	269.000	0.156%	0.653%	0.680%							
18		R#2	“24” 4595 PTB 09R#2	5.824	30.254	2838.0	268.700	0.156%	0.653%	0.680%							
19		final	“24” 4595 PTB 09final	5.824	30.248	2839.5	268.850	0.110%	0.653%	0.663%		0.006625	22782.27568	0.250000	0.000138	0.001651	
20																	
21	“39” 4596 PTB 09	R#1	“39” 4596 PTB 09R#1	5.892	30.816	2853.0	283.900	0.156%	0.653%	0.680%							
22		R#2	“39” 4596 PTB 09R#2	5.892	30.826	2849.0	284.400	0.156%	0.653%	0.680%							
23		final	“39” 4596 PTB 09final	5.892	30.821	2851.0	284.150	0.110%	0.653%	0.663%		0.006625	22782.27538	0.250000	0.000138	0.001651	
24																	
25	“42” 4597 PTB 09	R#1	“42” 4597 PTB 09R#1	5.880	30.713	2848.0	274.600	0.156%	0.653%	0.680%							
26		R#2	“42” 4597 PTB 09R#2	5.880	30.725	2844.0	277.100	0.156%	0.653%	0.680%							
27		final	“42” 4597 PTB 09final	5.880	30.719	2846.0	275.839	0.110%	0.653%	0.663%		0.006625	22782.26294	0.250000	0.000138	0.001651	
28																	
29	NSI 10	R#1	NSI 10R#1	5.890	31.962	2854.0	314.400	0.156%	0.653%	0.680%							
30		R#2	NSI 10R#2	5.890	31.944	2869.0	317.200	0.156%	0.653%	0.680%							
31		final	NSI 10final	5.890	31.953	2861.5	315.788	0.110%	0.653%	0.663%		0.006625	22782.26349	0.250000	0.000138	0.001651	
32																	
33						**Average NMISA Luminous Intensity relative standard uncertainty**						sum:	91129.07749	1.00000			
34							**NMISA**	0.028%	0.660%	0.661%							
35													**Final NMISA average relative standard uncertainty**				
36															**u-uncorr**	**u-corr**	**uf**
37														**NMISA**	0.0275%	0.6602%	0.6608%
38																	
39																	
40	NMI:	**NIM**															
41																	
42	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**NIM Lamp Luminous Intensity (cd)**					**Calculations for NIM weighted mean**					
43				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
44								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
45								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
46																	
47	NIM-01(Wi41/G-96)	R#1	NIM-01(Wi41/G-96)R#1	5.794	29.846	2837.0	253.145	0.035%	0.167%	0.171%							
48		R#2	NIM-01(Wi41/G-96)R#2	5.794	29.828	2837.0	252.660	0.057%	0.167%	0.176%							
49		final	NIM-01(Wi41/G-96)final	5.794	29.837	2837.0	253.012	0.030%	0.167%	0.170%		0.001696	347681.05909	0.197256	0.000029	0.000333	
50																	
51	NIM-02(Wi41/G-152)	R#1	NIM-02(Wi41/G-152)R#1	5.818	30.013	2829.0	263.580	0.032%	0.167%	0.170%							
52		R#2	NIM-02(Wi41/G-152)R#2	5.818	30.020	2829.0	263.925	0.057%	0.167%	0.177%							
53		final	NIM-02(Wi41/G-152)final	5.818	30.016	2829.0	263.660	0.028%	0.167%	0.169%		0.001693	349030.11258	0.198021	0.000027	0.000334	
54																	
55	NIM-03(Wi41/G-164)	R#1	NIM-03(Wi41/G-164)R#1	5.807	29.781	2841.0	275.150	0.008%	0.167%	0.167%							
56		R#2	NIM-03(Wi41/G-164)R#2	5.807	29.773	2841.0	275.600	0.048%	0.167%	0.174%							
57		final	NIM-03(Wi41/G-164)final	5.807	29.777	2841.0	275.164	0.008%	0.167%	0.167%		0.001672	357668.81541	0.202922	0.000008	0.000339	
58																	
59	NIM-04(Wi41/G-180)	R#1	NIM-04(Wi41/G-180)R#1	5.804	29.954	2839.0	265.172	0.020%	0.167%	0.168%							
60		R#2	NIM-04(Wi41/G-180)R#2	5.804	29.947	2839.0	265.620	0.043%	0.167%	0.172%							
61		final	NIM-04(Wi41/G-180)final	5.804	29.950	2839.0	265.251	0.018%	0.167%	0.168%		0.001680	354380.97063	0.201057	0.000018	0.000337	
62																	
63	NIM-05(Wi41/G-189)	R#1	NIM-05(Wi41/G-189)R#1	5.780	29.730	2840.0	269.570	0.024%	0.167%	0.169%							

Appendix_Cv2.1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
64		R#2	NIM-05(Wi41/G-189)R#2	5.780	29.711	2840.0	269.415	0.034%	0.167%	0.170%							
65		final	NIM-05(Wi41/G-189)final	5.780	29.721	2840.0	269.520	0.019%	0.167%	0.168%		0.001681	353828.27608	0.200743	0.000019	0.000337	
66																	
67						Average NIM Luminous Intensity relative standard uncertainty						sum:	1762589.23378	1.00000			
68							NIM	0.005%	0.168%	0.168%							
69													Final NIM average relative standard uncertainty:				
70															u-uncorr	u-corr	uf
71														NIM	0.0049%	0.1681%	0.1681%
72																	
73																	
74	NMI:	**NMIA**															
75																	
76	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**NMIA Lamp Luminous Intensity (cd)**					**Calculations for NMIA weighted mean**					
77				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
78								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
79								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
80																	
81	S7	R#1	S7R#1	5.780	31.724	2856.0	298.759	0.009%	0.153%	0.153%							
82		R#2	S7R#2	5.780	31.736	2856.0	298.716	0.008%	0.151%	0.151%							
83		final	S7final	5.780	31.730	2856.0	298.735	0.006%	0.152%	0.152%		0.001520	432773.37472	0.202861	0.000006	0.000308	
84																	
85	350 LI3	R#1	350 LI3R#1	5.794	31.741	2856.0	298.447	0.016%	0.153%	0.154%							
86		R#2	350 LI3R#2	5.794	31.751	2856.0	298.684	0.019%	0.151%	0.152%							
87		final	350 LI3final	5.794	31.746	2856.0	298.551	0.012%	0.152%	0.153%		0.001526	429240.69680	0.201205	0.000012	0.000307	
88																	
89	318 SI2	R#1	318 SI2R#1	5.781	31.722	2856.0	305.807	0.021%	0.153%	0.154%							
90		R#2	318 SI2R#2	5.781	31.736	2856.0	305.845	0.018%	0.151%	0.152%							
91		final	318 SI2final	5.781	31.729	2856.0	305.829	0.014%	0.152%	0.152%		0.001524	430298.79892	0.201701	0.000014	0.000307	
92																	
93	306 S15	R#1	306 S15R#1	5.858	32.078	2856.0	308.499	0.017%	0.153%	0.154%							
94		R#2	306 S15R#2	5.858	32.096	2856.0	308.601	0.016%	0.151%	0.152%							
95		final	306 S15final	5.858	32.087	2856.0	308.551	0.012%	0.152%	0.152%		0.001524	430540.03093	0.201814	0.000012	0.000307	
96																	
97	288 SI4	R#1	288 SI4R#1	5.786	31.672	2856.0	301.606	0.053%	0.153%	0.162%							
98		R#2	288 SI4R#2	5.786	31.668	2856.0	301.514	0.048%	0.151%	0.159%							
99		final	288 SI4final	5.786	31.670	2856.0	301.555	0.036%	0.152%	0.156%		0.001561	410497.16280	0.192419	0.000034	0.000298	
100																	
101						Average NMIA Luminous Intensity relative standard uncertainty						sum:	2133350.06417	1.00000			
102							NMIA	0.004%	0.153%	0.153%							
103													Final NMIA average relative standard uncertainty:				
104															u-uncorr	u-corr	uf
105														NMIA	0.0041%	0.1528%	0.1529%
106																	
107																	
108	NMI:	**NMIJ**															
109																	
110	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**NMIJ Lamp Luminous Intensity (cd)**					**Calculations for NMIJ weighted mean**					
111				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
112								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
113								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
114																	
115	#37	R#1	#37R#1	5.756	29.069	2800.0	242.145	0.090%	0.256%	0.271%							
116		R#2	#37R#2	5.756	29.064	2800.0	242.155	0.090%	0.256%	0.271%							
117		final	#37final	5.756	29.067	2800.0	242.150	0.064%	0.256%	0.264%		0.002638	143743.73352	0.200000	0.000064	0.000524	
118																	
119	#40	R#1	#40R#1	5.794	29.550	2800.0	250.505	0.090%	0.256%	0.271%							
120		R#2	#40R#2	5.794	29.544	2800.0	250.285	0.090%	0.256%	0.271%							
121		final	#40final	5.794	29.547	2800.0	250.395	0.064%	0.256%	0.264%		0.002638	143743.73173	0.200000	0.000064	0.000524	
122																	
123	#51	R#1	#51R#1	5.736	29.264	2800.0	240.850	0.090%	0.256%	0.271%							
124		R#2	#51R#2	5.736	29.262	2800.0	240.565	0.090%	0.256%	0.271%							
125		final	#51final	5.736	29.263	2800.0	240.707	0.064%	0.256%	0.264%		0.002638	143743.73045	0.200000	0.000064	0.000524	
126																	

Appendix_Cv2.1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
127	#52	R#1	#52R#1	5.765	29.167	2800.0	241.500	0.090%	0.256%	0.271%							
128		R#2	#52R#2	5.765	29.160	2800.0	241.490	0.090%	0.256%	0.271%							
129		final	#52final	5.765	29.163	2800.0	241.495	0.064%	0.256%	0.264%		0.002638	143743.73365	0.200000	0.000064	0.000524	
130																	
131	#58	R#1	#58R#1	5.610	29.970	2800.0	244.280	0.090%	0.256%	0.271%							
132		R#2	#58R#2	5.610	29.965	2800.0	244.505	0.090%	0.256%	0.271%							
133		final	#58final	5.610	29.967	2800.0	244.392	0.064%	0.256%	0.264%		0.002638	143743.73190	0.200000	0.000064	0.000524	
134																	
135						**Average NMIJ Luminous Intensity relative standard uncertainty**						sum:	718718.66125	1.00000			
136							**NMIJ**	0.014%	0.262%	0.262%							
137													**Final NMIJ average relative standard uncertainty:**				
138															**u-uncorr**	**u-corr**	**uf**
139														**NMIJ**	0.0142%	0.2618%	0.2622%
140																	
141																	
142	NMI:	**IO-CSIC**															
143																	
144	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**IO-CSIC Lamp Luminous Intensity (cd)**					**Calculations for IO-CSIC weighted mean**					
145				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
146								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
147								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
148																	
149	Wi95A	R#1	Wi95AR#1	5.836	30.807	2869.0	278.405	0.007%	0.310%	0.310%							
150		R#2	Wi95AR#2	5.836	30.930	2869.0	278.184	0.007%	0.310%	0.310%							
151		final	Wi95Afinal	5.836	30.868	2869.0	278.294	0.005%	0.310%	0.310%		0.003100	104032.63337	0.200005	0.000005	0.000620	
152																	
153	Wi95B	R#1	Wi95BR#1	5.836	31.083	2868.0	285.515	0.004%	0.310%	0.310%							
154		R#2	Wi95BR#2	5.837	31.127	2868.0	284.322	0.007%	0.310%	0.310%							
155		final	Wi95Bfinal	5.836	31.105	2868.0	285.188	0.003%	0.310%	0.310%		0.003100	104045.14922	0.200029	0.000003	0.000620	
156																	
157	Wi95C	R#1	Wi95CR#1	5.832	30.790	2862.0	286.693	0.003%	0.310%	0.310%							
158		R#2	Wi95CR#2	5.832	30.860	2862.0	286.268	0.007%	0.310%	0.310%							
159		final	Wi95Cfinal	5.832	30.825	2862.0	286.637	0.002%	0.310%	0.310%		0.003100	104051.55216	0.200042	0.000002	0.000620	
160																	
161	Wi95D	R#1	Wi95DR#1	5.836	30.587	2868.0	271.761	0.004%	0.310%	0.310%							
162		R#2	Wi95DR#2	5.836	30.633	2868.0	270.688	0.004%	0.310%	0.310%							
163		final	Wi95Dfinal	5.836	30.610	2868.0	271.222	0.003%	0.310%	0.310%		0.003100	104050.01451	0.200039	0.000003	0.000620	
164																	
165	A454	R#1	A454R#1	25.500	12.247	2844.0	433.167	0.013%	0.310%	0.310%							
166		R#2	A454R#2	25.501	12.267	2844.0	434.636	0.013%	0.310%	0.310%							
167		final	A454final	25.500	12.257	2844.0	433.899	0.009%	0.310%	0.310%		0.003101	103969.75394	0.199885	0.000009	0.000620	
168																	
169						**Average IO-CSIC Luminous Intensity relative standard uncertainty**						sum:	520149.10320	1.00000			
170							**IO-CSIC**	0.001%	0.310%	0.310%							
171													**Final IO-CSIC average relative standard uncertainty:**				
172															**u-uncorr**	**u-corr**	**uf**
173														**IO-CSIC**	0.0011%	0.3100%	0.3100%
174																	
175																	
176	NMI:	**LNE-CNAM**															
177																	
178	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**LNE-CNAM Lamp Luminous Intensity (cd)**					**Calculations for LNE-CNAM weighted mean**					
179				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
180								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
181								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
182																	
183	926	R#1	926R#1	5.690	29.010	2796.0	234.400	0.220%	0.220%	0.311%							
184		R#2	926R#2	5.690	28.970	2796.0	233.800	0.240%	0.220%	0.326%							
185		final	926final	5.690	28.990	2796.0	234.125	0.162%	0.220%	0.273%		0.002733	133868.05548	0.342036	0.000277	0.000893	
186																	
187	936	R#1	936R#1	5.690	29.150	2799.0	241.800	0.230%	0.220%	0.318%							
188		R#2	936R#2	5.690	29.100	2799.0	241.200	0.290%	0.220%	0.364%							
189		final	936final	5.690	29.125	2799.0	241.568	0.180%	0.220%	0.284%		0.002844	123649.59621	0.315928	0.000285	0.000852	

Appendix_Cv2.1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
190																	
191	A430	R#1	A430R#1	25.000	11.950	2815.0	397.300	0.220%	0.220%	0.311%							
192		R#2	A430R#2	25.000	11.960	2815.0	397.400	0.240%	0.220%	0.326%							
193		final	A430final	25.000	11.955	2815.0	397.346	0.162%	0.220%	0.273%		0.002733	133868.13157	0.342036	0.000277	0.000893	
194																	
195						**Average LNE-CNAM Luminous Intensity relative standard uncertainty**						sum:	391385.78326	1.00000			
196							**LNE-CNAM**	0.048%	0.264%	0.268%							
197													**Final LNE-CNAM average relative standard uncertainty:**				
198															**u-uncorr**	**u-corr**	**uf**
199														**LNE-CNAM**	0.0485%	0.2638%	0.2682%
200																	
201																	
202	NMI:	**METAS**															
203																	
204	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**METAS Lamp Luminous Intensity (cd)**					**Calculations for METAS weighted mean**					
205				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
206								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
207								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
208																	
209	506	R#1	506R#1	5.760	30.559	2855.7	276.229	0.038%	0.312%	0.315%							
210		R#2	506R#2	5.760	30.558	2855.7	276.193	0.038%	0.312%	0.315%							
211		final	506final	5.760	30.558	2855.7	276.211	0.027%	0.312%	0.314%		0.003135	101728.56832	0.166724	0.000022	0.000522	
212																	
213	684	R#1	684R#1	5.680	30.687	2854.4	277.966	0.048%	0.312%	0.316%							
214		R#2	684R#2	5.680	30.686	2854.4	277.881	0.038%	0.312%	0.315%							
215		final	684final	5.680	30.686	2854.4	277.914	0.030%	0.312%	0.314%		0.003138	101525.34990	0.166390	0.000025	0.000522	
216																	
217	841	R#1	841R#1	5.860	30.341	2858.3	280.875	0.038%	0.312%	0.315%							
218		R#2	841R#2	5.860	30.336	2858.3	280.311	0.037%	0.312%	0.315%							
219		final	841final	5.860	30.339	2858.3	280.587	0.027%	0.312%	0.314%		0.003135	101726.38529	0.166720	0.000022	0.000522	
220																	
221	1060	R#1	1060R#1	5.850	30.325	2841.0	272.256	0.038%	0.312%	0.315%							
222		R#2	1060R#2	5.850	30.338	2841.0	272.986	0.038%	0.312%	0.315%							
223		final	1060final	5.850	30.332	2841.0	272.627	0.027%	0.312%	0.314%		0.003136	101713.53497	0.166699	0.000022	0.000522	
224																	
225	1063	R#1	1063R#1	5.900	30.557	2854.5	283.982	0.038%	0.312%	0.315%							
226		R#2	1063R#2	5.900	30.568	2854.5	284.402	0.038%	0.312%	0.315%							
227		final	1063final	5.900	30.562	2854.5	284.197	0.027%	0.312%	0.314%		0.003136	101714.96298	0.166701	0.000022	0.000522	
228																	
229	1064	R#1	1064R#1	5.900	30.679	2854.8	287.908	0.037%	0.312%	0.315%							
230		R#2	1064R#2	5.900	30.692	2854.8	288.563	0.037%	0.312%	0.315%							
231		final	1064final	5.900	30.686	2854.8	288.232	0.026%	0.312%	0.313%		0.003135	101754.35247	0.166766	0.000022	0.000522	
232																	
233						**Average METAS Luminous Intensity relative standard uncertainty**						sum:	610163.15394	1.00000			
234							**METAS**	0.006%	0.313%	0.313%							
235													**Final METAS average relative standard uncertainty:**				
236															**u-uncorr**	**u-corr**	**uf**
237														**METAS**	0.0056%	0.3133%	0.3133%
238																	
239																	
240	NMI:	**NPL**															
241																	
242	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**NPL Lamp Luminous Intensity (cd)**					**Calculations for NPL weighted mean**					
243				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
244								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
245								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
246																	
247	A644	R#1	A644R#1	25.360	12.505	2850.0	451.78	0.082%	0.158%	0.178%							
248		R#2	A644R#2	25.360	12.500	2850.0	451.97	0.082%	0.158%	0.178%							
249		final	A644final	25.360	12.503	2850.0	451.87	0.058%	0.158%	0.168%		0.001683	353032.54775	0.208864	0.000061	0.000346	
250																	
251	A647	R#1	A647R#1	25.310	12.510	2850.0	459.43	0.082%	0.158%	0.178%							
252		R#2	A647R#2	25.310	12.533	2850.0	459.63	0.082%	0.158%	0.178%							

Appendix_Cv2.1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
253		final	A647final	25.310	12.522	2850.0	459.53	0.058%	0.158%	0.168%		0.001683	353032.54762	0.208864	0.000061	0.000346	
254																	
255	PA758	R#1	PA758R#1	25.220	12.743	2850.0	460.33	0.082%	0.158%	0.178%							
256		R#2	PA758R#2	25.220	12.751	2850.0	460.70	0.082%	0.158%	0.178%							
257		final	PA758final	25.220	12.747	2850.0	460.51	0.058%	0.158%	0.168%		0.001683	353032.54284	0.208864	0.000061	0.000346	
258																	
259	877	R#1	877R#1	5.818	30.013	2853.0	276.34	0.082%	0.158%	0.178%							
260		final	877final	5.818	30.013	2853.0	276.34	0.082%	0.158%	0.178%		0.001780	315576.87453	0.186704	0.000077	0.000323	
261																	
262	890	R#1	890R#1	5.804	29.871	2853.0	273.93	0.082%	0.158%	0.178%							
263		final	890final	5.804	29.871	2853.0	273.93	0.082%	0.158%	0.178%		0.001780	315576.87453	0.186704	0.000077	0.000323	
264																	
265						**Average NPL Luminous Intensity relative standard uncertainty**						sum:	1690251.38726	1.00000			
266							**NPL**	0.015%	0.169%	0.169%							
267													**Final NPL average relative standard uncertainty:**				
268															**u-uncorr**	**u-corr**	**uf**
269														**NPL**	0.0151%	0.1686%	0.1692%
270																	
271																	
272	NMI:	**PTB**															
273																	
274	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**PTB Lamp Luminous Intensity (cd)**					**Calculations for PTB weighted mean**					
275				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**					**Weights**		**Relative Uncertainties**		
276								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
277								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
278																	
279	759	R#1	759R#1	5.650	29.123	2800.0	236.210	0.120%	0.130%	0.180%							
280		R#2	759R#2	5.650	29.123	2800.0	236.220	0.130%	0.130%	0.180%							
281		final	759final	5.650	29.123	2800.0	236.215	0.088%	0.130%	0.157%		0.001571	405267.17848	0.164702	0.000073	0.000248	
282																	
283	791	R#1	791R#1	5.650	29.564	2800.0	247.550	0.120%	0.130%	0.180%							
284		R#2	791R#2	5.650	29.565	2800.0	247.530	0.120%	0.130%	0.180%							
285		final	791final	5.650	29.565	2800.0	247.540	0.085%	0.130%	0.155%		0.001552	414937.75913	0.168632	0.000072	0.000252	
286																	
287	793	R#1	793R#1	5.650	29.387	2800.0	245.970	0.120%	0.130%	0.180%							
288		R#2	793R#2	5.650	29.387	2800.0	246.000	0.130%	0.130%	0.180%							
289		final	793final	5.650	29.387	2800.0	245.984	0.088%	0.130%	0.157%		0.001571	405267.17807	0.164702	0.000073	0.000248	
290																	
291	848	R#1	848R#1	5.700	28.573	2810.0	228.530	0.120%	0.130%	0.180%							
292		R#2	848R#2	5.700	28.571	2810.0	228.540	0.120%	0.130%	0.180%							
293		final	848final	5.700	28.572	2810.0	228.535	0.085%	0.130%	0.155%		0.001552	414937.75928	0.168632	0.000072	0.000252	
294																	
295	851	R#1	851R#1	5.700	28.932	2815.0	233.490	0.120%	0.130%	0.180%							
296		R#2	851R#2	5.700	28.931	2815.0	233.540	0.120%	0.130%	0.180%							
297		final	851final	5.700	28.931	2815.0	233.515	0.085%	0.130%	0.155%		0.001552	414937.75792	0.168632	0.000072	0.000252	
298																	
299	858	R#1	858R#1	5.700	28.561	2800.0	225.120	0.120%	0.130%	0.180%							
300		R#2	858R#2	5.700	28.562	2800.0	225.010	0.130%	0.130%	0.180%							
301		final	858final	5.700	28.561	2800.0	225.069	0.088%	0.130%	0.157%		0.001571	405267.17096	0.164702	0.000073	0.000248	
302																	
303						**Average PTB Luminous Intensity relative standard uncertainty**						sum:	2460614.80383	1.00000			
304							**PTB**	0.018%	0.150%	0.151%							
305													**Final PTB average relative standard uncertainty:**				
306															**u-uncorr**	**u-corr**	**uf**
307														**PTB**	0.0177%	0.1500%	0.1511%
308																	
309																	
310	NMI:	**VNIIOFI**															
311																	
312	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**VNIIOFI Lamp Luminous Intensity (cd)**					**Calculations for VNIIOFI weighted mean**					
313				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**					**Weights**		**Relative Uncertainties**		
314								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
315								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		

Appendix_Cv2.1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
316																	
317	3281	R#1	3281R#1	5.8800	29.952	2853.9	273.480	0.060%	0.240%	0.250%							
318		R#2	3281R#2	5.8800	29.943	2853.9	275.060	0.060%	0.250%	0.260%							
319		final	3281final	5.8800	29.948	2853.9	274.265	0.042%	0.245%	0.249%		0.002486	161765.29098	0.166687	0.000035	0.000413	
320																	
321	3282	R#1	3282R#1	5.8000	30.547	2854.3	276.870	0.060%	0.240%	0.250%							
322		R#2	3282R#2	5.8000	30.541	2854.3	276.880	0.060%	0.250%	0.260%							
323		final	3282final	5.8000	30.544	2854.3	276.875	0.042%	0.245%	0.249%		0.002486	161746.98190	0.166668	0.000035	0.000413	
324																	
325	N 01	R#1	N 01R#1	5.8800	30.419	2855.8	287.190	0.060%	0.240%	0.250%							
326		R#2	N 01R#2	5.8800	30.413	2855.8	286.540	0.060%	0.250%	0.260%							
327		final	N 01final	5.8800	30.416	2855.8	286.864	0.042%	0.245%	0.249%		0.002487	161739.59856	0.166660	0.000035	0.000413	
328																	
329	N 02	R#1	N 02R#1	5.9000	30.647	2854.1	285.880	0.060%	0.240%	0.250%							
330		R#2	N 02R#2	5.9000	30.637	2854.1	285.180	0.060%	0.250%	0.260%							
331		final	N 02final	5.9000	30.642	2854.1	285.529	0.042%	0.245%	0.249%		0.002487	161739.00241	0.166660	0.000035	0.000413	
332																	
333	N 03	R#1	N 03R#1	5.9200	30.594	2853.6	284.510	0.060%	0.240%	0.250%							
334		R#2	N 03R#2	5.9200	30.583	2853.6	283.690	0.060%	0.250%	0.260%							
335		final	N 03final	5.9200	30.589	2853.6	284.099	0.042%	0.245%	0.249%		0.002487	161737.60655	0.166658	0.000035	0.000413	
336																	
337	N 04	R#1	N 04R#1	5.8700	30.487	2856.6	284.040	0.060%	0.240%	0.250%							
338		R#2	N 04R#2	5.8700	30.485	2856.6	284.050	0.060%	0.250%	0.260%							
339		final	N 04final	5.8700	30.486	2856.6	284.045	0.042%	0.245%	0.249%		0.002486	161746.97898	0.166668	0.000035	0.000413	
340																	
341						**Average VNIIOFI Luminous Intensity relative standard uncertainty**						sum:	970475.45939	1.00000			
342							**VNIIOFI**	0.009%	0.248%	0.248%							
343													**Final VNIIOFI average relative standard uncertainty:**				
344															**u-uncorr**	**u-corr**	**uf**
345														**VNIIOFI**	0.0087%	0.2477%	0.2479%
346																	
347																	
348	NMI:	**NIST**															
349																	
350	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**NIST Lamp Luminous Intensity (cd)**					**Calculations for NIST weighted mean**					
351				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
352								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
353								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
354																	
355	NIST20100	R#1	NIST20100R#1	5.822	30.270	2855.0	283.000	0.149%	0.200%	0.249%							
356		R#2	NIST20100R#2	5.822	30.260	2853.0	282.600	0.110%	0.200%	0.228%							
357		final	NIST20100final	5.822	30.265	2854.0	282.742	0.089%	0.200%	0.219%		0.002188	208939.93383	0.175990	0.000078	0.000377	
358																	
359	NIST20101	R#1	NIST20101R#1	5.918	30.600	2856.0	287.300	0.178%	0.200%	0.268%							
360		R#2	NIST20101R#2	5.918	30.600	2855.0	287.500	0.163%	0.200%	0.258%							
361		final	NIST20101final	5.918	30.600	2855.5	287.409	0.120%	0.200%	0.233%		0.002333	183709.21591	0.154738	0.000093	0.000349	
362																	
363	NIST20102	R#1	NIST20102R#1	5.905	30.440	2855.0	288.500	0.136%	0.200%	0.242%							
364		R#2	NIST20102R#2	5.905	30.430	2854.0	288.300	0.202%	0.200%	0.285%							
365		final	NIST20102final	5.905	30.435	2854.5	288.438	0.113%	0.200%	0.230%		0.002297	189581.00531	0.159684	0.000090	0.000355	
366																	
367	NIST20103	R#1	NIST20103R#1	5.877	30.510	2858.0	286.600	0.136%	0.200%	0.242%							
368		R#2	NIST20103R#2	5.877	30.500	2856.0	285.900	0.142%	0.200%	0.245%							
369		final	NIST20103final	5.877	30.505	2857.0	286.265	0.098%	0.200%	0.223%		0.002228	201384.13264	0.169626	0.000083	0.000369	
370																	
371	NIST20104	R#1	NIST20104R#1	5.683	30.700	2858.0	272.700	0.136%	0.200%	0.242%							
372		R#2	NIST20104R#2	5.683	30.700	2857.0	272.200	0.136%	0.200%	0.242%							
373		final	NIST20104final	5.683	30.700	2857.5	272.450	0.096%	0.200%	0.222%		0.002219	203045.65317	0.171025	0.000082	0.000371	
374																	
375	NIST20105	R#1	NIST20105R#1	5.922	30.590	2859.0	291.400	0.163%	0.200%	0.258%							
376		R#2	NIST20105R#2	5.922	30.590	2857.0	290.800	0.125%	0.200%	0.236%							
377		final	NIST20105final	5.922	30.590	2858.0	291.023	0.099%	0.200%	0.223%		0.002233	200565.53657	0.168936	0.000084	0.000368	
378																	

Appendix_Cv2.1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
379						**Average NIST Luminous Intensity relative standard uncertainty**						sum:	1187225.47744	1.00000			
380							**NIST**	0.021%	0.219%	0.220%							
381													**Final NIST average relative standard uncertainty:**				
382															**u-uncorr**	**u-corr**	**uf**
383														**NIST**	0.0209%	0.2188%	0.2198%
384																	
385																	
386	NMI:	**NRC**															
387																	
388	**Lamp#**	**Round#**	**Data ID**	**Lamp Electrical**		**Lamp CCT**	**NRC Lamp Luminous Intensity (cd)**					**Calculations for NRC weighted mean**					
389				**Current(A)**	**Voltage(V)**	**K**	**I(cd)**	**Relative Standard Uncertainty**				**Weights**			**Relative Uncertainties**		
390								**random**	**systematic**	**final lamp (uf)**		**uf**	**1/(uf)^2**	**wi**	**uncorrelated**	**correlated**	
391								**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**		**fractional**		**normalised**	**for combining lamps**		
392																	
393	NRC021	final	NRC021final	5.661	30.356	2800.0	254.400	0.100%	0.605%	0.614%		0.006135	26568.73431	0.166667	0.000083	0.001019	
394																	
395	NRC022	final	NRC022final	5.620	30.069	2800.0	251.600	0.100%	0.605%	0.614%		0.006135	26568.73431	0.166667	0.000083	0.001019	
396																	
397	NRC023	final	NRC023final	5.635	30.211	2800.0	254.000	0.100%	0.605%	0.614%		0.006135	26568.73431	0.166667	0.000083	0.001019	
398																	
399	NRC026	final	NRC026final	5.650	30.398	2800.0	252.200	0.100%	0.605%	0.614%		0.006135	26568.73431	0.166667	0.000083	0.001019	
400																	
401	NRC027	final	NRC027final	5.665	30.461	2800.0	254.600	0.100%	0.605%	0.614%		0.006135	26568.73431	0.166667	0.000083	0.001019	
402																	
403	NRC030	final	NRC030final	5.633	30.106	2800.0	253.800	0.100%	0.605%	0.614%		0.006135	26568.73431	0.166667	0.000083	0.001019	
404																	
405						**Average NRC Luminous Intensity relative standard uncertainty**						sum:	159412.40587	1.00000			
406							**NRC**	0.020%	0.611%	0.612%							
407													**Final NRC average relative standard uncertainty:**				
408															**u-uncorr**	**u-corr**	**uf**
409														**NRC**	0.0204%	0.6115%	0.6118%

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	**CCPR-K3.2014: Luminous Intensity**																				
2	**Draft B Report**																				
3	**2020-October-15**																				
4	**Appendix Dv2.1**																				
5	**Summary of Pilot Measurements of Participant Lamps**																				
6																					
7																					
8					Lamp uncertainties are for combining																
9					individual lamp measurements							Lamp uncertainties are for combining									
10	NMI:	**NMISA**										all NMISA lamp measurements									
11																					
12	**Lamp#**	**Round#**	**Data ID**		**NMISA Lamp Luminous Intensity**			**Pilot Measurements**				**Combined Uncertainty u(*R(i,j)*)**				**Calculations for NMISA+Pilot weighted means**					
13				**I(cd)**	**Relative Standard Uncertainty**			*R(i,j)*	**Relative Standard Uncertainty**			**Relative Standard Uncertainty**					**Weights**		**Relative Uncertainties**		
14					**random**	**systematic**	**final lamp (uf)**	**<cd/V>**	**u-uncorr**	**u-corr**	**u-uncorr(lamp)**	**uncorrelated**	**correlated**	**combined uT**		**uT**	**1/(uT)^2**	**wi**	**uncorrelated**	**correlated**	
15					**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**									**cd/V**		**normalised**			
16																					
17	"24" 4595 PTB 09	final	"24" 4595 PTB 09final	268.850	0.110%	0.653%	0.663%	85.224989	0.000429	0.000122	0.000889	0.099%	0.663%	0.670%		0.57096	3.067497	0.248890932	0.000246	0.001649	
18	"39" 4596 PTB 09	final	"39" 4596 PTB 09final	284.150	0.110%	0.653%	0.663%	85.421999	0.000429	0.000122	0.000752	0.087%	0.663%	0.668%		0.57085	3.068722	0.248990335	0.000216	0.001650	
19	"42" 4597 PTB 09	final	"42" 4597 PTB 09final	275.839	0.110%	0.653%	0.663%	85.339987	0.000429	0.000122	0.000143	0.045%	0.663%	0.664%		0.56681	3.112634	0.252553309	0.000114	0.001674	
20	NSI 10	final	NSI 10final	315.788	0.110%	0.653%	0.663%	85.824098	0.000429	0.000122	0.000215	0.048%	0.663%	0.664%		0.57019	3.075809	0.249565424	0.000120	0.001654	
21																					
22			**NMISA Summary**													sum:	12.32466	1.00000			
23			**NMISA-weighted mean:**				*R(i)=*	85.452603													
24			**Uncertainties**														**Final NMISA + Pilot relative standard uncertainty:**				
25			NMISA		0.0275%	0.6602%	0.6608%												**u-uncorr**	**u-corr**	**uf**
26			**NMISA + Pilot (u(Ri))**		0.0366%	0.6626%	0.6636%											**NMISA + Pilot**	0.0366%	0.6626%	0.6636%
27			NMISA_transfer				0.0614%														
28												Lamp uncertainties are for combining									
29	NMI:	**NIM**										all NIM lamp measurements									
30																					
31	**Lamp#**	**Round#**	**Data ID**		**NIM Lamp Luminous Intensity**			**Pilot Measurements**				**Combined Uncertainty u(*R(i,j)*)**				**Calculations for NIM+Pilot weighted means**					
32				**I(cd)**	**Relative Standard Uncertainty**			*R(i,j)*	**Relative Standard Uncertainty**			**Relative Standard Uncertainty**					**Weights**				
33					**random**	**systematic**	**final lamp (uf)**	**<cd/V>**	**u-uncorr**	**u-corr**	**u-uncorr(lamp)**	**u-uncorr**	**u-corr**	**combined uT**		**uT**	**1/(uT)^2**	**wi**	**wi*u-uncorr**	**wi*u-corr**	
34					**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**									**cd/V**		**normalised**			
35																					
36	NIM-01(Wi41/G-96)	final	NIM-01(Wi41/G-96)final	253.012	0.030%	0.167%	0.170%	86.340464	0.000429	0.000122	0.000887	0.099%	0.170%	0.197%		0.16966	34.74019	0.218689827	0.000215	0.000372	
37	NIM-02(Wi41/G-152)	final	NIM-02(Wi41/G-152)final	263.660	0.028%	0.167%	0.169%	86.225685	0.000429	0.000122	0.002458	0.249%	0.170%	0.302%		0.26016	14.77449	0.093005545	0.000232	0.000158	
38	NIM-03(Wi41/G-164)	final	NIM-03(Wi41/G-164)final	275.164	0.008%	0.167%	0.167%	86.202028	0.000429	0.000122	0.001285	0.136%	0.168%	0.216%		0.18582	28.96062	0.182307413	0.000247	0.000306	
39	NIM-04(Wi41/G-180)	final	NIM-04(Wi41/G-180)final	265.251	0.018%	0.167%	0.168%	86.090246	0.000429	0.000122	0.000221	0.048%	0.168%	0.175%		0.15083	43.95691	0.276709193	0.000133	0.000466	
40	NIM-05(Wi41/G-189)	final	NIM-05(Wi41/G-189)final	269.520	0.019%	0.167%	0.168%	86.490125	0.000429	0.000122	0.000803	0.091%	0.169%	0.192%		0.16569	36.42377	0.229288022	0.000209	0.000386	
41																					
42			**NIM Summary**													sum:	158.85598	1.00000			
43			**NIM-weighted mean:**				*R(i)=*	86.269629													
44			**Uncertainties**														**Final NIM + Pilot relative standard uncertainty:**				
45			NIM		0.0049%	0.1681%	0.1681%												**u-uncorr**	**u-corr**	**uf**
46			**NIM + Pilot (u(Ri))**		0.0472%	0.1688%	0.1753%											**NIM + Pilot**	0.0472%	0.1688%	0.1753%
47			NIM_transfer				0.0494%														
48												Lamp uncertainties are for combining									
49	NMI:	**NMIA**										all NMIA lamp measurements									
50																					
51	**Lamp#**	**Round#**	**Data ID**		**NMIA Lamp Luminous Intensity**			**Pilot Measurements**				**Combined Uncertainty u(*R(i,j)*)**				**Calculations for NMIA+Pilot weighted means**					
52				**I(cd)**	**Relative Standard Uncertainty**			*R(i,j)*	**Relative Standard Uncertainty**			**Relative Standard Uncertainty**					**Weights**				
53					**random**	**systematic**	**final lamp (uf)**	**<cd/V>**	**u-uncorr**	**u-corr**	**u-uncorr(lamp)**	**u-uncorr**	**u-corr**	**combined uT**		**uT**	**1/(uT)^2**	**wi**	**wi*u-uncorr**	**wi*u-corr**	
54					**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**									**cd/V**		**normalised**			
55																					
56	S7	final	S7final	298.735	0.006%	0.152%	0.152%	85.962034	0.000429	0.000122	0.001042	0.113%	0.152%	0.190%		0.16298	37.64564	0.16301544	0.000184	0.000249	
57	350 LI3	final	350 LI3final	298.551	0.012%	0.152%	0.153%	86.046121	0.000429	0.000122	0.000256	0.050%	0.153%	0.161%		0.13859	52.06672	0.225462458	0.000113	0.000345	
58	318 SI2	final	318 SI2final	305.829	0.014%	0.152%	0.152%	86.140581	0.000429	0.000122	0.000835	0.094%	0.153%	0.179%		0.15455	41.86359	0.181280261	0.000170	0.000277	
59	306 S15	final	306 S15final	308.551	0.012%	0.152%	0.152%	86.125138	0.000429	0.000122	0.000505	0.066%	0.153%	0.167%		0.14350	48.55967	0.210276009	0.000139	0.000321	
60	288 SI4	final	288 SI4final	301.555	0.036%	0.152%	0.156%	86.200848	0.000429	0.000122	0.000120	0.045%	0.157%	0.163%		0.14031	50.79737	0.219965832	0.000098	0.000344	
61																					
62			**NMIA Summary**													sum:	230.93300	1.00000			
63			**NMIA-weighted mean:**				*R(i)=*	86.100187													
64			**Uncertainties**														**Final NMIA + Pilot relative standard uncertainty:**				
65			NMIA		0.0041%	0.1528%	0.1529%												**u-uncorr**	**u-corr**	**uf**
66			**NMIA + Pilot (u(Ri))**		0.0323%	0.1537%	0.1571%											**NMIA + Pilot**	0.0323%	0.1537%	0.1571%
67			NMIA_transfer				0.0360%														
68												Lamp uncertainties are for combining									
69	NMI:	**NMIJ**										all NMIJ lamp measurements									
70																					
71	**Lamp#**	**Round#**	**Data ID**		**NMIJ Lamp Luminous Intensity**			**Pilot Measurements**				**Combined Uncertainty u(*R(i,j)*)**				**Calculations for NMIJ+Pilot weighted means**					
72				**I(cd)**	**Relative Standard Uncertainty**			*R(i,j)*	**Relative Standard Uncertainty**			**Relative Standard Uncertainty**					**Weights**				
73					**random**	**systematic**	**final lamp (uf)**	**<cd/V>**	**u-uncorr**	**u-corr**	**u-uncorr(lamp)**	**u-uncorr**	**u-corr**	**combined uT**		**uT**	**1/(uT)^2**	**wi**	**wi*u-uncorr**	**wi*u-corr**	
74					**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**									**cd/V**		**normalised**			
75																					
76	#37	final	#37final	242.150	0.064%	0.256%	0.264%	86.638944	0.000350	0.000122	0.001108	0.116%	0.264%	0.288%		0.24994	16.00753	0.176760272	0.000205	0.000467	
77	#40	final	#40final	250.395	0.064%	0.256%	0.264%	86.682269	0.000350	0.000122	0.000056	0.035%	0.264%	0.266%		0.23093	18.75147	0.207059735	0.000073	0.000547	

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
78	#51	final	#51final	240.707	0.064%	0.256%	0.264%	86.701927	0.000350	0.000122	0.000303	0.046%	0.264%	0.268%		0.23242	18.51144	0.204409186	0.000095	0.000540	
79	#52	final	#52final	241.495	0.064%	0.256%	0.264%	86.668812	0.000350	0.000122	0.000297	0.046%	0.264%	0.268%		0.23227	18.53537	0.204673479	0.000094	0.000540	
80	#58	final	#58final	244.392	0.064%	0.256%	0.264%	86.601076	0.000350	0.000122	0.000123	0.037%	0.264%	0.267%		0.23091	18.75488	0.207097328	0.000077	0.000547	
81																					
82			NMIJ Summary													sum:	90.56070	1.00000			
83			NMIJ-weighted mean:				*R(i)=*	86.659060													
84			Uncertainties														Final NMIJ + Pilot relative standard uncertainty:				
85			NMIJ		0.0142%	0.2618%	0.2622%												u-uncorr	u-corr	uf
86			NMIJ + Pilot (u(Ri))		0.0267%	0.2640%	0.2654%											NMIJ + Pilot	0.0267%	0.2640%	0.2654%
87			NMIJ_transfer				0.0408%														
88												Lamp uncertainties are for combining									
89	NMI:	IO-CSIC										all IO-CSIC lamp measurements									
90																					
91	Lamp#	Round#	Data ID		IO-CSIC Lamp Luminous Intensity			Pilot Measurements				Combined Uncertainty u(*R(i,j)*)				Calculations for IO-CSIC+Pilot weighted means					
92				I(cd)	Relative Standard Uncertainty			*R(i,j)*	Relative Standard Uncertainty			Relative Standard Uncertainty					Weights				
93					random	systematic	final lamp (uf)	<cd/V>	u-uncorr	u-corr	u-uncorr(lamp)	u-uncorr	u-corr	combined uT		uT	1/(uT)^2	wi	wi*u-uncorr	wi*u-corr	
94					u-uncorr	u-corr	SQRT(u-uncorr^2 + u-corr^2)									cd/V		normalised			
95																					
96	Wi95A	final	Wi95Afinal	278.294	0.005%	0.310%	0.310%	86.199291	0.000429	0.000122	0.000807	0.091%	0.310%	0.323%		0.27881	12.86417	0.195292059	0.000178	0.000606	
97	Wi95B	final	Wi95Bfinal	285.188	0.003%	0.310%	0.310%	86.162482	0.000429	0.000122	0.000959	0.105%	0.310%	0.328%		0.28224	12.55373	0.190579163	0.000200	0.000591	
98	Wi95C	final	Wi95Cfinal	286.637	0.002%	0.310%	0.310%	86.229941	0.000429	0.000122	0.000322	0.054%	0.310%	0.315%		0.27150	13.56655	0.205955007	0.000110	0.000639	
99	Wi95D	final	Wi95Dfinal	271.222	0.003%	0.310%	0.310%	85.980405	0.000429	0.000122	0.000633	0.076%	0.310%	0.320%		0.27474	13.24842	0.201125343	0.000154	0.000624	
100	A454	final	A454final	433.899	0.009%	0.310%	0.310%	86.239028	0.000459	0.000122	0.000123	0.048%	0.310%	0.314%		0.27078	13.63858	0.207048428	0.000098	0.000643	
101																					
102			IO-CSIC Summary													sum:	65.87145	1.00000			
103			IO-CSIC-weighted mean:				*R(i)=*	86.162792													
104			Uncertainties														Final IO-CSIC + Pilot relative standard uncertainty:				
105			IO-CSIC		0.0011%	0.3100%	0.3100%												u-uncorr	u-corr	uf
106			IO-CSIC + Pilot (u(Ri))		0.0343%	0.3103%	0.3122%											IO-CSIC + Pilot	0.0343%	0.3103%	0.3122%
107			IO-CSIC_transfer				0.0365%														
108												Lamp uncertainties are for combining									
109	NMI:	LNE-CNAM										all LNE-CNAM lamp measurements									
110																					
111	Lamp#	Round#	Data ID		LNE-CNAM Lamp Luminous Intensity			Pilot Measurements				Combined Uncertainty u(*R(i,j)*)				Calculations for LNE-CNAM+Pilot weighted means					
112				I(cd)	Relative Standard Uncertainty			*R(i,j)*	Relative Standard Uncertainty			Relative Standard Uncertainty					Weights				
113					random	systematic	final lamp (uf)	<cd/V>	u-uncorr	u-corr	u-uncorr(lamp)	u-uncorr	u-corr	combined uT		uT	1/(uT)^2	wi	wi*u-uncorr	wi*u-corr	
114					u-uncorr	u-corr	SQRT(u-uncorr^2 + u-corr^2)									cd/V		normalised			
115																					
116	926	final	926final	234.125	0.162%	0.220%	0.273%	87.151593	0.000350	0.000122	0.000890	0.096%	0.274%	0.290%		0.25258	15.67491	0.373165218	0.000357	0.001021	
117	936	final	936final	241.568	0.180%	0.220%	0.284%	88.029666	0.000350	0.000122	0.002348	0.237%	0.285%	0.371%		0.32629	9.392788	0.223609635	0.000531	0.000636	
118	A430	final	A430final	397.346	0.162%	0.220%	0.273%	87.423860	0.000459	0.000122	0.000171	0.049%	0.274%	0.278%		0.24298	16.93759	0.403225148	0.000197	0.001103	
119																					
120			Summary													sum:	42.00529	1.00000			
121			LNE-CNAM-weighted mean:				*R(i)=*	87.457723													
122			Uncertainties														Final LNE-CNAM + Pilot relative standard uncertainty:				
123			LNE-CNAM		0.0485%	0.2638%	0.2682%												u-uncorr	u-corr	uf
124			LNE-CNAM + Pilot (u(Ri))		0.0669%	0.2761%	0.2841%											LNE-CNAM + Pilot	0.0669%	0.2761%	0.2841%
125			LNE-CNAM_transfer				0.0936%														
126												Lamp uncertainties are for combining									
127	NMI:	METAS										all METAS lamp measurements									
128																					
129	Lamp#	Round#	Data ID		METAS Lamp Luminous Intensity			Pilot Measurements				Combined Uncertainty u(*R(i,j)*)				Calculations for METAS+Pilot weighted means					
130				I(cd)	Relative Standard Uncertainty			*R(i,j)*	Relative Standard Uncertainty			Relative Standard Uncertainty					Weights				
131					random	systematic	final lamp (uf)	<cd/V>	u-uncorr	u-corr	u-uncorr(lamp)	u-uncorr	u-corr	combined uT		uT	1/(uT)^2	wi	wi*u-uncorr	wi*u-corr	
132					u-uncorr	u-corr	SQRT(u-uncorr^2 + u-corr^2)									cd/V		normalised			
133																					
134	506	final	506final	276.211	0.027%	0.312%	0.314%	86.258517	0.000429	0.000122	0.000121	0.045%	0.314%	0.317%		0.27337	13.38156	0.169279687	0.000075	0.000531	
135	684	final	684final	277.914	0.030%	0.312%	0.314%	86.112881	0.000429	0.000122	0.000012	0.043%	0.314%	0.317%		0.27298	13.42002	0.169766281	0.000073	0.000533	
136	841	final	841final	280.587	0.027%	0.312%	0.314%	86.381991	0.000429	0.000122	0.000413	0.060%	0.314%	0.319%		0.27587	13.1396	0.166218887	0.000099	0.000522	
137	1060	final	1060final	272.627	0.027%	0.312%	0.314%	86.190786	0.000429	0.000122	0.000602	0.074%	0.314%	0.322%		0.27786	12.9524	0.163850777	0.000121	0.000514	
138	1063	final	1063final	284.197	0.027%	0.312%	0.314%	86.229931	0.000429	0.000122	0.000732	0.085%	0.314%	0.325%		0.28030	12.72808	0.161013003	0.000137	0.000505	
139	1064	final	1064final	288.232	0.026%	0.312%	0.313%	86.068002	0.000429	0.000122	0.000163	0.046%	0.314%	0.317%		0.27289	13.42833	0.169871366	0.000078	0.000533	
140																					
141			Summary													sum:	79.04999	1.00000			
142			METAS-weighted mean:				*R(i)=*	86.206253													
143			Uncertainties														Final METAS + Pilot relative standard uncertainty:				
144			METAS		0.0056%	0.3133%	0.3133%												u-uncorr	u-corr	uf
145			METAS + Pilot (u(Ri))		0.0245%	0.3138%	0.3148%											METAS + Pilot	0.0245%	0.3138%	0.3148%
146			METAS_transfer				0.0301%														
147												Lamp uncertainties are for combining									
148	NMI:	NPL										all NPL lamp measurements									
149																					
150	Lamp#	Round#	Data ID		NPL Lamp Luminous Intensity			Pilot Measurements				Combined Uncertainty u(*R(i,j)*)				Calculations for NPL+Pilot weighted means					
151				I(cd)	Relative Standard Uncertainty			*R(i,j)*	Relative Standard Uncertainty			Relative Standard Uncertainty					Weights				
152					random	systematic	final lamp (uf)	<cd/V>	u-uncorr	u-corr	u-uncorr(lamp)	u-uncorr	u-corr	combined uT		uT	1/(uT)^2	wi	wi*u-uncorr	wi*u-corr	
153					u-uncorr	u-corr	SQRT(u-uncorr^2 + u-corr^2)									cd/V		normalised			
154																					

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
155	A644	final	A644final	451.875	0.058%	0.158%	0.168%	86.471175	0.000459	0.000122	0.000566	0.073%	0.169%	0.184%		0.15895	39.58029	0.198756516	0.000145	0.000335	
156	A647	final	A647final	459.530	0.058%	0.158%	0.168%	86.503670	0.000459	0.000122	0.000293	0.054%	0.169%	0.177%		0.15338	42.50903	0.213463522	0.000116	0.000360	
157	PA758	final	PA758final	460.515	0.058%	0.158%	0.168%	86.629919	0.000459	0.000122	0.000516	0.069%	0.169%	0.182%		0.15795	40.0844	0.201287989	0.000139	0.000340	
158	877	final	877final	276.340	0.082%	0.158%	0.178%	86.585864	0.000429	0.000122	0.000376	0.057%	0.178%	0.187%		0.16219	38.01411	0.190891815	0.000109	0.000341	
159	890	final	890final	273.930	0.082%	0.158%	0.178%	86.559634	0.000429	0.000122	0.000243	0.049%	0.178%	0.185%		0.16023	38.95173	0.195600158	0.000096	0.000349	
160																					
161			NPL Summary													sum:	199.13957	1.00000			
162			NPL-weighted mean:				*R(i)=*	86.549260													
163			Uncertainties														Final NPL + Pilot relative standard uncertainty:				
164			NPL		0.0151%	0.1686%	0.1692%												u-uncorr	u-corr	uf
165			NPL + Pilot (u(Ri))		0.0274%	0.1725%	0.1746%											NPL + Pilot	0.0274%	0.1725%	0.1746%
166			NPL_transfer				0.0431%														
167												Lamp uncertainties are for combining									
168	NMI:	PTB										all PTB lamp measurements									
169																					
170	Lamp#	Round#	Data ID		PTB Lamp Luminous Intensity			Pilot Measurements				Combined Uncertainty u(*R(i,j)*)				Calculations for PTB+Pilot weighted means					
171				I(cd)	Relative Standard Uncertainty			*R(i,j)*	Relative Standard Uncertainty			Relative Standard Uncertainty					Weights				
172					random	systematic	final lamp (uf)	<cd/V>	u-uncorr	u-corr	u-uncorr(lamp)	u-uncorr	u-corr	combined uT		uT	1/(uT)^2	wi	wi*u-uncorr	wi*u-corr	
173					u-uncorr	u-corr	SQRT(u-uncorr^2 + u-corr^2)									cd/V		normalised			
174																					
175	759	final	759final	236.215	0.088%	0.130%	0.157%	86.234506	0.000429	0.000122	0.000609	0.075%	0.158%	0.174%		0.15030	44.26968	0.158817616	0.000118	0.000250	
176	791	final	791final	247.540	0.085%	0.130%	0.155%	86.189513	0.000429	0.000122	0.000138	0.045%	0.156%	0.162%		0.13972	51.22315	0.183763219	0.000083	0.000286	
177	793	final	793final	245.984	0.088%	0.130%	0.157%	86.260429	0.000429	0.000122	0.000818	0.092%	0.158%	0.183%		0.15755	40.28643	0.144527687	0.000134	0.000228	
178	848	final	848final	228.535	0.085%	0.130%	0.155%	86.239953	0.000429	0.000122	0.000435	0.061%	0.156%	0.167%		0.14425	48.06017	0.172416019	0.000105	0.000268	
179	851	final	851final	233.515	0.085%	0.130%	0.155%	86.233833	0.000429	0.000122	0.000637	0.077%	0.156%	0.174%		0.14972	44.61168	0.160044535	0.000123	0.000249	
180	858	final	858final	225.069	0.088%	0.130%	0.157%	86.204822	0.000429	0.000122	0.000096	0.044%	0.158%	0.164%		0.14101	50.29429	0.180430924	0.000079	0.000284	
181																					
182			Summary													sum:	278.74541	1.00000			
183			PTB-weighted mean:				*R(i)=*	86.225460													
184			Uncertainties														Final PTB + Pilot relative standard uncertainty:				
185			PTB		0.0177%	0.1500%	0.1511%												u-uncorr	u-corr	uf
186			PTB + Pilot (u(Ri))		0.0267%	0.1566%	0.1589%											PTB + Pilot	0.0267%	0.1566%	0.1589%
187			PTB_transfer				0.0491%														
188												Lamp uncertainties are for combining									
189	NMI:	VNIIOFI										all VNIIOFI lamp measurements									
190																					
191	Lamp#	Round#	Data ID		VNIIOFI Lamp Luminous Intensity			Pilot Measurements				Combined Uncertainty u(*R(i,j)*)				Calculations for VNIIOFI+Pilot weighted means					
192				I(cd)	Relative Standard Uncertainty			*R(i,j)*	Relative Standard Uncertainty			Relative Standard Uncertainty					Weights				
193					random	systematic	final lamp (uf)	<cd/V>	u-uncorr	u-corr	u-uncorr(lamp)	u-uncorr	u-corr	combined uT		uT	1/(uT)^2	wi	wi*u-uncorr	wi*u-corr	
194					u-uncorr	u-corr	SQRT(u-uncorr^2 + u-corr^2)									cd/V		normalised			
195																					
196	3281	final	3281final	274.265	0.042%	0.245%	0.249%	85.590866	0.000429	0.000122	0.001309	0.138%	0.249%	0.285%		0.24353	16.86199	0.15936868	0.000220	0.000397	
197	3282	final	3282final	276.875	0.042%	0.245%	0.249%	85.734964	0.000429	0.000122	0.001173	0.125%	0.249%	0.279%		0.23880	17.53544	0.16573364	0.000207	0.000413	
198	N 01	final	N 01final	286.864	0.042%	0.245%	0.249%	85.588783	0.000429	0.000122	0.000448	0.062%	0.249%	0.257%		0.21959	20.73790	0.19600125	0.000122	0.000488	
199	N 02	final	N 02final	285.529	0.042%	0.245%	0.249%	85.709032	0.000429	0.000122	0.001196	0.127%	0.249%	0.279%		0.23955	17.42616	0.16470088	0.000209	0.000410	
200	N 03	final	N 03final	284.099	0.042%	0.245%	0.249%	85.502599	0.000429	0.000122	0.002160	0.220%	0.249%	0.332%		0.28421	12.37983	0.11700620	0.000258	0.000291	
201	N 04	final	N 04final	284.045	0.042%	0.245%	0.249%	85.591162	0.000429	0.000122	0.000402	0.059%	0.249%	0.256%		0.21893	20.86361	0.19718936	0.000116	0.000491	
202																					
203			Summary													sum:	105.80493	1.00000			
204			VNIIOFI-weighted mean:				*R(i)=*	85.623532													
205			Uncertainties														Final VNIIOFI + Pilot relative standard uncertainty:				
206			VNIIOFI		0.0087%	0.2477%	0.2479%												u-uncorr	u-corr	uf
207			VNIIOFI + Pilot (u(Ri))		0.0479%	0.2489%	0.2535%											VNIIOFI + Pilot	0.0479%	0.2489%	0.2535%
208			VNIIOFI_transfer				0.0531%														
209												Lamp uncertainties are for combining									
210	NMI:	NIST										all NIST lamp measurements									
211																					
212	Lamp#	Round#	Data ID		NIST Lamp Luminous Intensity			Pilot Measurements				Combined Uncertainty u(*R(i,j)*)				Calculations for NIST+Pilot weighted means					
213				I(cd)	Relative Standard Uncertainty			*R(i,j)*	Relative Standard Uncertainty			Relative Standard Uncertainty					Weights				
214					random	systematic	final lamp (uf)	<cd/V>	u-uncorr	u-corr	u-uncorr(lamp)	u-uncorr	u-corr	combined uT		uT	1/(uT)^2	wi	wi*u-uncorr	wi*u-corr	
215					u-uncorr	u-corr	SQRT(u-uncorr^2 + u-corr^2)									cd/V		normalised			
216																					
217	NIST20100	final	NIST20100final	282.742	0.089%	0.200%	0.219%	86.302305	0.000429	0.000122	0.000969	0.106%	0.219%	0.243%		0.21005	22.66487	0.156983006	0.000166	0.000344	
218	NIST20101	final	NIST20101final	287.409	0.120%	0.200%	0.233%	86.265433	0.000429	0.000122	0.000848	0.095%	0.234%	0.252%		0.21756	21.12687	0.146330347	0.000139	0.000342	
219	NIST20102	final	NIST20102final	288.438	0.113%	0.200%	0.230%	86.368920	0.000429	0.000122	0.000123	0.045%	0.230%	0.234%		0.20235	24.42365	0.169164733	0.000075	0.000389	
220	NIST20103	final	NIST20103final	286.265	0.098%	0.200%	0.223%	86.304520	0.000429	0.000122	0.000280	0.051%	0.223%	0.229%		0.19761	25.60772	0.17736598	0.000091	0.000396	
221	NIST20104	final	NIST20104final	272.450	0.096%	0.200%	0.222%	86.344087	0.000429	0.000122	0.000096	0.044%	0.222%	0.227%		0.19562	26.13128	0.180992258	0.000080	0.000402	
222	NIST20105	final	NIST20105final	291.023	0.099%	0.200%	0.223%	86.240820	0.000429	0.000122	0.000566	0.071%	0.224%	0.235%		0.20235	24.42349	0.169163677	0.000120	0.000378	
223																					
224			Summary													sum:	144.37788	1.00000			
225			NIST-weighted mean:				*R(i)=*	86.305732													
226			Uncertainties														Final NIST + Pilot relative standard uncertainty:				
227			NIST		0.0209%	0.2188%	0.2198%												u-uncorr	u-corr	uf
228			NIST + Pilot (u(Ri))		0.0286%	0.2251%	0.2269%											NIST + Pilot	0.0286%	0.2251%	0.2269%
229			NIST_transfer				0.0563%														
230												Lamp uncertainties are for combining									
231	NMI:	NRC										all NRC lamp measurements									

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
232																					
233	**Lamp#**	**Round#**	**Data ID**	**NRC Lamp Luminous Intensity**				**Pilot Measurements**				**Combined Uncertainty u(*R(i,j)*)**				**Calculations for NRC+Pilot weighted means**					
234				**I(cd)**	**Relative Standard Uncertainty**			*R(i,j)*	**Relative Standard Uncertainty**			**Relative Standard Uncertainty**					**Weights**				
235					**random**	**systematic**	**final lamp (uf)**	**<cd/V>**	**u-uncorr**	**u-corr**	**u-uncorr(lamp)**	**u-uncorr**	**u-corr**	**combined uT**		**uT**	**1/(uT)^2**	**wi**	**wi*u-uncorr**	**wi*u-corr**	
236					**u-uncorr**	**u-corr**	**SQRT(u-uncorr^2 + u-corr^2)**									**cd/V**		**normalised**			
237																					
238	NRC021	final	NRC021final	254.400	0.100%	0.605%	0.614%	86.710956	0.000303	0.000122	0.000663	0.073%	0.614%	0.618%		0.53582	3.48310	0.165944	0.000121	0.001018	
239	NRC022	final	NRC022final	251.600	0.100%	0.605%	0.614%	86.432845	0.000303	0.000122	0.000604	0.068%	0.614%	0.617%		0.53358	3.51242	0.167341	0.000113	0.001027	
240	NRC023	final	NRC023final	254.000	0.100%	0.605%	0.614%	86.667211	0.000303	0.000122	0.000168	0.035%	0.614%	0.615%		0.53266	3.52457	0.167920	0.000058	0.001030	
241	NRC026	final	NRC026final	252.200	0.100%	0.605%	0.614%	86.838748	0.000303	0.000122	0.000788	0.084%	0.614%	0.619%		0.53789	3.45635	0.164669	0.000139	0.001010	
242	NRC027	final	NRC027final	254.600	0.100%	0.605%	0.614%	86.676055	0.000303	0.000122	0.000294	0.042%	0.614%	0.615%		0.53312	3.51843	0.167627	0.000071	0.001029	
243	NRC030	final	NRC030final	253.800	0.100%	0.605%	0.614%	86.872708	0.000303	0.000122	0.000413	0.051%	0.614%	0.616%		0.53492	3.49476	0.166499	0.000085	0.001022	
244																					
245			**Summary**													sum:	20.98962	1.00000			
246			**NRC-weighted mean:**				*R(i)=*	86.699196													
247			**Uncertainties**														**Final NRC + Pilot relative standard uncertainty:**				
248			NRC		0.0204%	0.6115%	0.6118%												**u-uncorr**	**u-corr**	**uf**
249			**NRC + Pilot (u(Ri))**		0.0250%	0.6136%	0.6141%											**NRC + Pilot**	0.0250%	0.6136%	0.6141%
250			NRC_transfer				0.0534%														

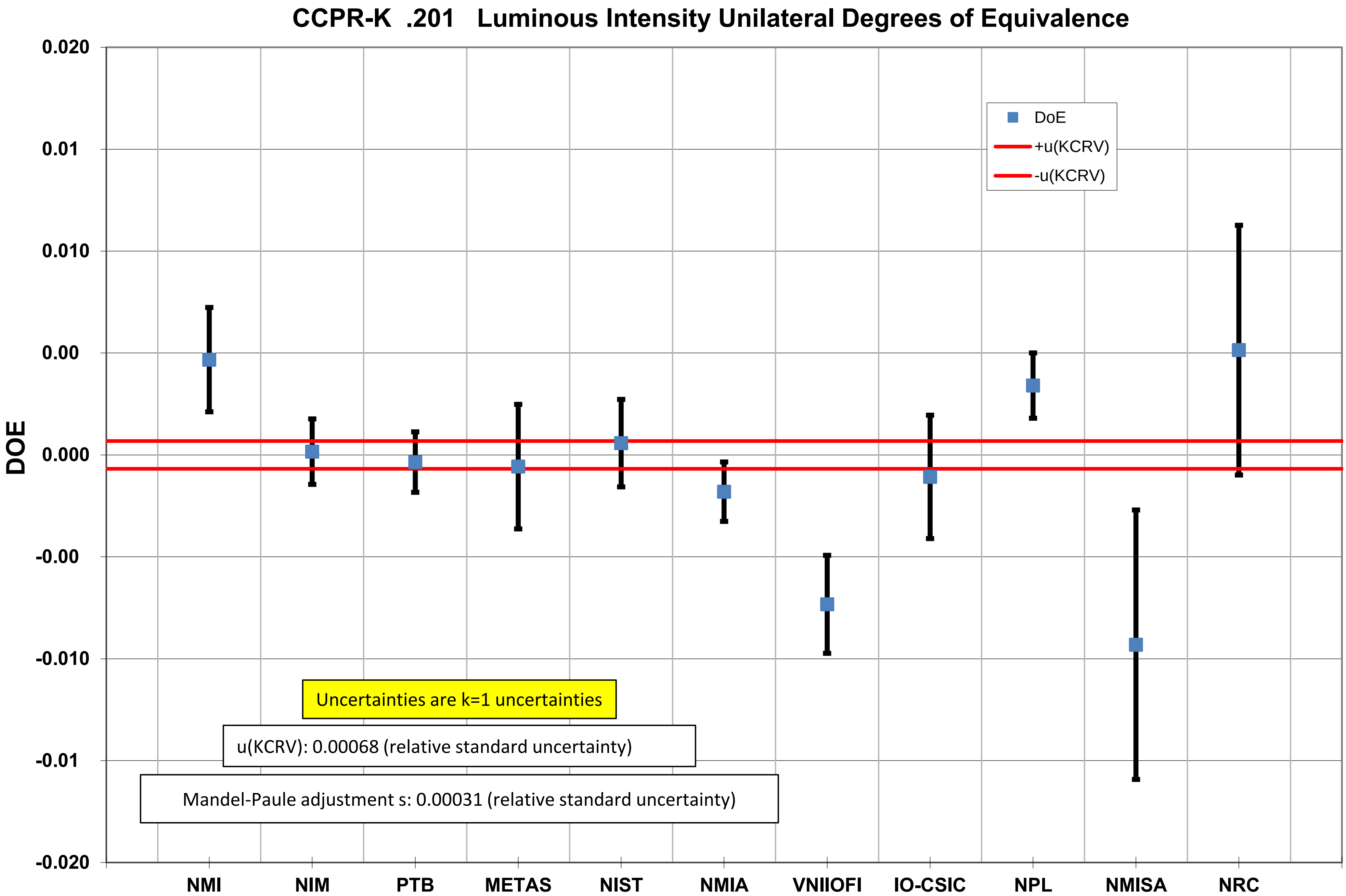
Appendix_Ev2.1

	A	B	C	D	E	F	G	H
1	**CCPR-K3.2014: Luminous Intensity**							
2	**Draft B Report**							
3	**2020-October-15**							
4	**Appendix Ev2.1**							
5	**Calculation of the KCRV and the Unilateral DoE**							
6							0.0006163	Draft Av1.0 value
7							0.0003400	Draft Av2.0 value
8						**Mandel-Paule adjustment s:**	0.0003100	(relative standard uncertainty)
9								
10								
11				**Relative Standard Uncertainties**			**Uncertainty u(c,t,s)**	
12		**NMI**	**R(i)**	**u(NMI)**	**uc(NMI)**	**Pilot Transfer**	**cutoff NMI+transfer+s**	
13			**cd/V**	**no cutoff**	**with cutoff**	**u(t)**	**relative standard**	**cd/V**
14								
15								
16	1	NMIJ	86.659060	0.002622	0.002622	0.000408	0.002672	0.231546
17	2	NIM	86.269629	0.001681	0.001722	0.000494	0.001818	0.156878
18	3	PTB	86.225460	0.001511	0.001722	0.000491	0.001818	0.156726
19	4	METAS	86.206253	0.003133	0.003133	0.000301	0.003163	0.272672
20	5	NIST	86.305732	0.002198	0.002198	0.000563	0.002290	0.197679
21	6	NMIA	86.100187	0.001529	0.001722	0.000360	0.001787	0.153834
22	7	VNIIOFI	85.623532	0.002479	0.002479	0.000531	0.002554	0.218685
23	8	IO-CSIC	86.162792	0.003100	0.003100	0.000365	0.003137	0.270298
24	9	NPL	86.549260	0.001692	0.001722	0.000431	0.001802	0.155991
25	10	NMISA	85.452603	0.006608	0.006608	0.000614	0.006644	0.567723
26	11	NRC	86.699196	0.006118	0.006118	0.000534	0.006149	0.533124
27								
28			median NMI uncertainty:	0.002339				**SUM(wi):**
29			cutoff uncertainty:	0.001722				
30								
31		**KCRV:**	**86.255839**	**cd/V**				
32		**u(KCRV):**	0.058794	**cd/V**				
33		**u(KCRV):**	0.000682	(relative standard uncertainty)				
34								
35		**for plot text box:**	Mandel-Paule adjustment s: 0.00031 (relative standard uncertainty)					
36			u(KCRV): 0.00068 (relative standard uncertainty)					
37								
38		for plot:	0.0	0.000682	-0.000682			
39			12.0	0.000682	-0.000682			
40				0.000682	-0.000682			
41				0.000682	-0.000682			
42				0.000682	-0.000682			
43				0.000682	-0.000682			
44				0.000682	-0.000682			
45				0.000682	-0.000682			
46				0.000682	-0.000682			
47				0.000682	-0.000682			
48				0.000682	-0.000682			
49				0.000682	-0.000682			
50				0.000682	-0.000682			

	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
10												**Unilateral DoE**				
11			**KCRV uncertainty calculation**				**Outlier Test**			**Chi-square**		**Unilateral DoE**	**ui(Di) for k=1**			
12	**KCRV weights wi**		**u(R(i))=u(NMI)+u(t)**		**wi*u(R(i))**		**R(i)-KCRV**	**(R(i)-KCRV)/u(NMI)**		**(R(i)-KCRV)^2/u(c,t,s)^2**		**Di**	**correlation term**	**ui(Di)**	**k=1**	
13	**1/u(c,t,s)^2**	**normalised**	**relative Standard**	**cd/V**	**cd/V**		**cd/V**			16.906950		**(Ri-KCRV)/KCRV**	**cd/V**		**ui(Di)/KCRV**	**Di/ui**
16	18.652039	0.071599	0.002654	0.229982	0.016467		0.403221	1.77		3.032584		0.004675	0.007574	0.220850	0.002560	1.8258
17	40.632629	0.155976	0.001753	0.151194	0.023583		0.013790	0.10		0.007727		0.000160	0.007131	0.138511	0.001606	0.0996
18	40.711690	0.156280	0.001589	0.136982	0.021408		-0.030379	-0.23		0.037572		-0.000352	0.005865	0.127891	0.001483	-0.2375
19	13.449899	0.051630	0.003148	0.271359	0.014010		-0.049586	-0.18		0.033070		-0.000575	0.007604	0.263608	0.003056	-0.1881
20	25.590523	0.098234	0.002269	0.195860	0.019240		0.049893	0.26		0.063704		0.000578	0.007537	0.185152	0.002147	0.2695
21	42.256726	0.162211	0.001571	0.135221	0.021934		-0.155652	-1.18		1.023773		-0.001805	0.005932	0.125736	0.001458	-1.2379
22	20.910394	0.080269	0.002535	0.217068	0.017424		-0.632307	-2.98		8.360223		-0.007331	0.007564	0.207391	0.002404	-3.0489
23	13.687225	0.052541	0.003122	0.268975	0.014132		-0.093046	-0.35		0.118499		-0.001079	0.007602	0.261155	0.003028	-0.3563
24	41.095974	0.157755	0.001746	0.151156	0.023846		0.293421	2.00		3.538205		0.003402	0.007209	0.138189	0.001602	2.1233
25	0.000000	0.000000	0.006636	0.567105	0.000000		-0.803236	-1.42		0.000000		-0.009312	0.000000	0.570144	0.006610	-1.4088
26	3.518389	0.013506	0.006141	0.532446	0.007191		0.443357	0.84		0.691594		0.005140	0.007658	0.528486	0.006127	0.8389
28	260.505487	1.000000		**u(KCRV):**	0.058794											

Appendix_Fv2.1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
1	**CCPR-K3.2014: Luminous Intensity**																										
2	**Draft B Report**																										
3	**2020-October-15**																										
4	**Appendix Fv2.1**																										
5	**Calculation of the Bilateral DoE (uij, k=1)**																										
6		**ui and uij are k=1 uncertainties**																									
7																											
8																											
9					**j:**	**IO-CSIC**		**METAS**		**NIM**		**NIST**		**NMIA**		**NMIJ**		**NMISA**		**NPL**		**NRC**		**PTB**		**VNIIOFI**	
10	**i**	**NMI**	**Di**	**ui**		**Dij**	**uij**	**Dij**	**uij**	**Dij**	**uij**	**Dij**	**uij**	**Dij**	**uij**	**Dij**	**uij**	**Dij**	**uij**	**Dij**	**uij**	**Dij**	**uij**	**Dij**	**uij**	**Dij**	**uij**
11	1	IO-CSIC	-0.001079	0.003028				-0.000504	0.004433	-0.001239	0.003580	-0.001657	0.003859	0.000726	0.003494	-0.005753	0.004097	0.008234	0.007334	-0.004480	0.003577	-0.006219	0.006889	-0.000727	0.003503	0.006252	0.004021
12	2	METAS	-0.000575	0.003056		0.000504	0.004433			-0.000735	0.003603	-0.001153	0.003881	0.001230	0.003518	-0.005250	0.004117	0.008737	0.007345	-0.003977	0.003600	-0.005715	0.006901	-0.000223	0.003526	0.006756	0.004042
13	3	NIM	0.000160	0.001606		0.001239	0.003580	0.000735	0.003603			-0.000419	0.002867	0.001964	0.002353	-0.004515	0.003180	0.009472	0.006864	-0.003242	0.002474	-0.004980	0.006386	0.000512	0.002365	0.007490	0.003082
14	4	NIST	0.000578	0.002147		0.001657	0.003859	0.001153	0.003881	0.000419	0.002867			0.002383	0.002760	-0.004096	0.003492	0.009891	0.007014	-0.002823	0.002864	-0.004562	0.006547	0.000931	0.002770	0.007909	0.003403
15	5	NMIA	-0.001805	0.001458		-0.000726	0.003494	-0.001230	0.003518	-0.001964	0.002353	-0.002383	0.002760			-0.006479	0.003084	0.007508	0.006820	-0.005206	0.002349	-0.006945	0.006339	-0.001452	0.002234	0.005526	0.002982
16	6	NMIJ	0.004675	0.002560		0.005753	0.004097	0.005250	0.004117	0.004515	0.003180	0.004096	0.003492	0.006479	0.003084			0.013987	0.007147	0.001273	0.003177	-0.000465	0.006690	0.005027	0.003093	0.012005	0.003670
17	7	NMISA	-0.009312	0.006610		-0.008234	0.007334	-0.008737	0.007345	-0.009472	0.006864	-0.009891	0.007014	-0.007508	0.006820	-0.013987	0.007147			-0.012714	0.006862	-0.014452	0.009042	-0.008960	0.006824	-0.001982	0.007104
18	8	NPL	0.003402	0.001602		0.004480	0.003577	0.003977	0.003600	0.003242	0.002474	0.002823	0.002864	0.005206	0.002349	-0.001273	0.003177	0.012714	0.006862			-0.001738	0.006385	0.003754	0.002361	0.010732	0.003078
19	9	NRC	0.005140	0.006127		0.006219	0.006889	0.005715	0.006901	0.004980	0.006386	0.004562	0.006547	0.006945	0.006339	0.000465	0.006690	0.014452	0.009042	0.001738	0.006385			0.005492	0.006343	0.012471	0.006644
20	10	PTB	-0.000352	0.001483		0.000727	0.003503	0.000223	0.003526	-0.000512	0.002365	-0.000931	0.002770	0.001452	0.002234	-0.005027	0.003093	0.008960	0.006824	-0.003754	0.002361	-0.005492	0.006343			0.006978	0.002992
21	11	VNIIOFI	-0.007331	0.002404		-0.006252	0.004021	-0.006756	0.004042	-0.007490	0.003082	-0.007909	0.003403	-0.005526	0.002982	-0.012005	0.003670	0.001982	0.007104	-0.010732	0.003078	-0.012471	0.006644	-0.006978	0.002992		


CCPR-K .201 Luminous Intensity Unilateral Degrees of Equivalence
0.020
0.01
0.010
0.00
0.000
-0.00
-0.010
-0.01
-0.020
DOE
DoE
+u(KCRV)
-u(KCRV)
Uncertainties are k=1 uncertainties
u(KCRV): 0.00068 (relative standard uncertainty)
Mandel-Paule adjustment s: 0.00031 (relative standard uncertainty)
NMI
NIM
PTB
METAS
NIST
NMIA
VNIIOFI
IO-CSIC
NPL
NMISA
NRC