EURAMET.PR-K4.3

Bilateral comparison of luminous flux

Final Report, February 2019

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Content

1. INTRODUCTION

This report describes the bilateral comparison “EURAMET.PR-K4.3” on luminous flux. This key comparison was carried out under the auspices of the European Association of National Metrology Institutes (EURAMET), which is the Regional Metrology Organisation (RMO) in Europe. According to paragraphs T.8 and T.9 of the MRA, a bilateral key comparison is to be carried out between two institutes as outlined in CIPM Guideline for key comparisons [1]. The scheme for performing comparisons within the framework of EURAMET is presented in Euramet Guidelines on Conducting Comparisons [2]. RMO key comparisons in the field of photometry and radiometry are performed in accordance with the Guidelines for CCPR and RMO Bilateral Key Comparisons (CCPR-G5) [3] and Guidelines for RMO PR Key Comparisons (CCPR-G6) [4].

In 1997, the Comite International des Poids et Mesures (CIPM) had initialized two key comparisons CCPR-K3a of luminous intensity and CCPR-K4 of luminous flux with the Physikalisch-Technische Bundesanstalt, Germany, acting as pilot laboratory. The maintained units of 16 national metrological laboratories and of the Bureau International des Poids et Mesures (BIPM) were compared in a ‘star-type’ structure, using more than 200 lamps as transfer standards. The results of these comparisons are key comparison reference values (KCRV) for the two quantities. All results were published[1] in 1999 and the DOEs are listed in the data base [5] of the Bureau Internationale des Poids et Mesures (BIPM).

In 2010, under the auspices of the European Association of National Metrology Institutes (EURAMET) as the Regional Metrology Organisation (RMO) two international key comparisons on luminous intensity (EURAMET.PR-K3.a) and luminous flux (EURAMET.PR-K4) were carried out [6]. The units are transferred by batches of incandescent lamps from the participants to the pilot laboratory, the Physikalisch-Technische Bundesanstalt (PTB). When it was decided to carry out the EURAMET Key Comparison, the Institute National de Métrologie (BNM-INM / CNAM, France) and the Instituto Nazionale di Ricerca Metrologica (INRIM, Italy) agreed to act as link laboratories for both units. Key comparisons are intended to determine the Degrees of Equivalence (DOE) for each non-link participant and the associated expanded uncertainty. The DOE for a quantity states for a participant the relative difference of his value with the related Key Comparison Reference Value (KCRV).

On the bases of the referenced documents, the luminous flux comparison between IO-CSIC and TUBITAK UME was carried out within the scope of EURAMET.PR-K4.3, whose technical protocol was approved by WG-KC of CCPR in December 2016. IO-CSIC (Spain) acts as pilot and linking laboratory (CSIC participated in CCPR-K4)[1] for this comparison. This bilateral comparison is intended to determine the Degree of Equivalence (DoE) for TUBITAK UME (Turkey) and its associated expanded uncertainty. The DoE sets the relative difference of the TUBITAK UME measurement results to the Key Comparison Reference Value (KCRV), which was determined in the CCPR-K4 key comparison.
Since CCPR-K4, KCRV are maintained by the participants of CCPR-K4. IO-CSIC transfers its maintained values by a set of lamps to TUBITAK UME.

A third party (CCPR-WG-KC Secretary) was designated for the comparison, and all the measurement results, both from the non-link laboratory and the linking laboratory were submitted to the third party upon completion of each measurement cycle, to ensure blindness of the comparison. At completion of all measurements, the third party sent all the data received to the linking laboratory.

1.- Note that at the time of CCPR-K4 comparison the name was IFA-CSIC

This document reports the final results of the bilateral comparison of luminous flux between CSIC and TUBITAK UME, and comparison with the EURAMET-RV and the DOEs. All main information, the data collection and the evaluation are given in the following sections, and are supplemented with more details in the Apendix.

2. GENERAL INFORMATION

2.1. List of Participants

The acronyms of the participating are listed in the first column of Table 1. The names of the institute and the contact person with the e-mail address are given in the second column. The third column shows the country and the city of each participant. In the last column, role of each laboratory is entered.

Acronym	**Laboratory name** ***Contact person / Email***	**Country** ***City***	**Role**
CSIC	Instituto de Optica, CSIC *Alicia Pons, Email : alicia.pons@csic.es*	Spain *Madrid*	Pilot
TUBITAK UME	Ulusal Metroloji Enstitüsü, TUBITAK UME Ferhat Sametoglu, *Email : ferhat.sametoglu@tubitak.gov.tr*	Turkey *Kocaeli*	Participant

2.2. Time Schedule

Preparation of full protocol agreed by participants was finished in November 2016 and protocol and notification of the comparison were sent to EURAMET TC-PR Chairman in December 2016. In June 2017, the protocol was approved by CCPR-WG-KC and registered at KCDB. After that, the first measurements of four luminous flux lamp standards were performed at TUBITAK UME between June 2017 and July 2017 and then information about the measurement results with expanded uncertainties were sent to the third party (Joële Viallon, jviallon@bipm.org) via email. After that the lamps were sent to CSIC. Measurements at CSIC were performed in September 2017 and information about the measurement results with expanded uncertainties were sent to the third party (Joële Viallon, jviallon@bipm.org) via email. Subsequently, the lamps were returned to TUBITAK UME, in where the second measurements were performed in November 2017 and obtained results were sent to third party (Joële Viallon, jviallon@bipm.org) via email.
After collection of all the results, the third party sent all the data to the pilot laboratory (CSIC), which implemented Pre-Draft A procedures.
When the Pre-Draft A procedures were completed in December 2017, CSIC prepared the Draft A report following the CCPR Guideline G5 "Guidelines for CCPR and RMO Bilateral Key Comparisons".

2.3. Lamp-Transfer-Standard

The measurement artefacts were specially developed transfer standard lamps (four items, numbers of which are 250, 352, 353 and 355) for luminous flux of the Polaron LF200W type, the image of which is shown in Fig. 1. The use of these lamps was decided and determined by the participants on request of TUBITAK UME.

Additional information of the LF200W lamps is as follows:

- Lamp base: E27 Edison scree base.
- Nominal luminous flux: 2500 lm.
- Rated operating current: around 2 A. Rated operating voltage: around 90 V.
- Typical value of CCT (or distribution temperature): 2715 K.

Figure 1. Image of transfer standard lamp (Polaron LF200W) used within this comparison.

2.4. Measurement Conditions

The measurand was luminous flux of a lamp. This photometric quantity was measured for the defined operating conditions of each lamp, where the operating current acted as the setting parameter. The lamps were powered by a DC power supply with the polarity as it was defined at TUBITAK UME. The exact values of the lamps operating current were also supplied by TUBITAK UME. The lamp voltage was measured to monitor the lamp stability, using a 4-pole technique directly at the lamp cap. The measurements were carried out under appropriate laboratory conditions with the room temperature staying between 20 ºC and 25 ºC. The room temperature, the operating DC current and the lamp voltage were recorded and reported together with the measured luminous flux values.
The luminous flux of the lamps was measured independently at least 2 times. Each independent measurement was carried out for the lamp being realigned in the measurement facility and being switched off and on after a break of at least 1 h for each lamp.
In both laboratories, all lamps were measured using an integrating sphere photometer. The lamps were vertically installed in the center of the sphere, the lamp cap pointing upwards. The photometer head used with the sphere did not receive direct radiation from the lamp. The lamps were aligned following the usual laboratory procedures.
Before installing in the facility, the lamps were inspected for damage or contamination of the lamp bulb or cap. No damage or contamination was recorded during the comparison.

No drift of the traveling lamps was noticed during the period of the comparison. Therefore no drift correction and corresponding uncertainty were applied.

3. MEASUREMENTS PERFORMED AT TUBITAK UME

The basic components of the measurement system, which is shown in Fig. 2, are an integrating sphere with a baffle screen, a calibrated cosine-corrected photometer head and an auxiliary lamp [7].

The integrating sphere is equipped with an interchangeable lamp holder and a screw-based E27 socket. Reference and the DUT lamps were mounted to the centre of the sphere and operated alternately. The illuminance inside the sphere generated by each lamp was measured by using a cosine corrected photometer head, which has a V(λ)-corrected silicon photodiode with a cosine-corrected angular responsivity. During the measurements, the photometer temperature was monitored and the photometer signal was corrected for temperature change by using a calibrated Photocurrentmeter.

A screen was used between the photometer head and the light source to avoid direct illumination from light source, In order to minimize the spatial non-uniformity, the screen was located to 1/3 the sphere radius from the photometer head. Integrating sphere is equipped with an auxiliary lamp to measure self-absorption of the sphere with installed lamps, which is located onto the sphere wall opposite to the photometer head.

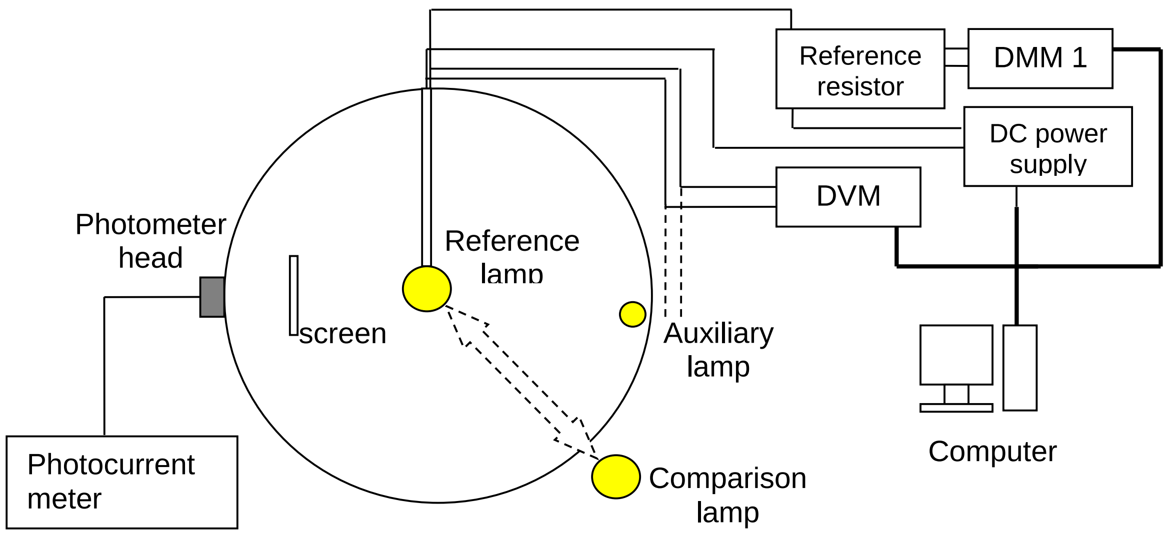

Fig. 2. Luminous Flux Measurement System of TUBITAK UME

3.1. Geometric Conditions

The relative luminous flux values were measured by using the integrating sphere, which has 2.0 m in diameter.

The luminous flux lamps were operated under the following conditions:

- lamps were mounted to the centre of the sphere
- lamp axis (cap up) was vertical
- auxiliary lamp was located on the sphere wall opposite from the photometer head
- all the light emitted by the lamp was measured.

3.2 Electrical Conditions

Luminous flux lamps were operated with DC power at fixed polarity (negative polarity was connected to the central tip of the socket and positive polarity was connected to the screwed edge) and at stabilized lamp current to get better accuracy of electrical measurements. Highly stable PTN 150-20 type Heinzinger power supply with a nominal stability of 10^{-5} A was operated on a constant-current mode. In any case, the electrical parameters of lamp were measured using four-pole-technique, which is shown in the comparison protocol. The lamp current was measured as the voltage across a calibrated reference resistor. The lamp current and voltage were recorded by using calibrated HP 3456A multimeter (DMM) and Datron Wavetek 1271 model digital voltmeter. The electrical measurements were acquired by a personal computer, in where developed software based on LabView was used for controlling the lamp current automatically and record electrical parameters during measurements.

3.3. Thermodynamic Conditions

The ambient temperature inside the integrating sphere was monitored by a Pt-100 temperature sensor, which was installed in the sphere at the same height of the lamp. The sensor was placed behind this baffle in order to shield the direct illumination of the lamp. During the measurements, the stability of thermodynamic conditions was recorded. The ambient temperature and the humidity were (23.0 ± 2.0) °C and (45.0±10.0)% rh, respectively.

3.4. Temporal Conditions

The lamp currents were adjusted to ramp up (and ramp down at the end) slowly to the rated value in around 90 sec in each set of measurement. Measurements were started approximately after 12 minutes warm-up time while ensuring that stability has been achieved. Data measurements took within 2-3 minutes after this stabilization time, thus resulting a lamp run-time period of around 15 min. Luminous flux value of each of the lamp was reached through a three separate repeat set of measurements while remounting and reburning the lamps in each case. In each set, twelve consecutive values were recorded for averaging by shielding or opening the light way.

3.5. Determination of the Luminous Flux

Two Polaron LF200L type of lamps, which were calibrated at TUBITAK UME by using an absolute integration sphere method, were taken as reference lamps. Before to determine the luminous flux value of the comparison lamps self-absorption factor of the integrating sphere with the reference and comparison lamps (DUTs) were measured by means of an auxiliary lamp. To ensure that the integrating sphere condition has not changed during the measurement the measurement sequence was selected as follows: reference-DUT-reference. For the control and stabilization of the current, a LabView based feedback control system was developed and used. The lamp current was measured to be stable at around 4×10^{-5} A. After the auxiliary lamp was stabilized, mean photocurrent readings (y_{ar} and y_{ac}) generated at the output of the photometer head (when the referece and DUT lamps were installed) and mean voltage reading (V_{ja}) of the auxiliary lamp were recorded. When the auxiliary lamp was turned off, the dark photocurrent reading was taken and substructed from the measured y_{ar} and y_{ac} in order to determine real photocurrents. Then the first reference lamp was installed to the lamp holder and operated by appling the required electrical current to the lamp. After the lamp stabilization process, the mean photocurrent reading (y_r) generated at the output of the photometer head and mean voltage reading (V_{jr}) of the lamp were recorded and lamp current was switched off via ramp down process. After that the reference lamp was replaced with the first DUT and operated by appling the required electrical current to the lamp. After the lamp stabilization process of the DUT, the mean photocurrent reading (y_c) generated at the output of the photometer head and mean voltage reading (V_{jc}) were recorded and then DUT current was switched off. After this measurements the first reference lamp was installed again and the same procedure was repeated again. The same process was repeated also for the second reference lamp and the mean luminous flux value for each of the DUT was calculated mathematically.

The luminous flux value was determined by using the following equation:

$$\Phi_c = (\Phi_r - \delta\Phi_r) \cdot \left(\frac{y_c}{y_r}\right) \cdot \left(\frac{y_{ar}}{y_{ac}}\right) \cdot \left(\frac{T_c}{T_r}\right)^{m_s} \cdot \left(\frac{J_{rm}}{J_{rs}}\right)^{-m_i} \cdot \left(\frac{J_{cm}}{J_{cs}}\right)^{m_i} \cdot (1 - P_{nl} - P_t - G_a)$$

where, *r* and *c* subscrits denotes parameters related to the reference and the DUT, Φ_r is the luminous flux value of the reference lamp (lm), $\delta\Phi_r$ is the drift of the reference luminous flux lamp between recalibrations (lm), y_c is the mean photocurrent generated at the output of the photometer head while the DUT was operated (nA), y_r is the mean photocurrent generated at the output of the photometer head while the reference lamp was operated (nA), y_{ar} is the mean photocurrent generated at the output of the photometer head while the self absorption factor measurement with the reference lamp was performed (nA), y_{ac} is the mean photocurrent generated at the output of the photometer head while the self absorption factor measurement with the DUT was performed (nA), T_c is the color temperature of the DUT (K), T_r is the color temperature of the reference lamp (K), m_s is the mismatch index of the sphere photometer, m_i is the exponent for changes of the lamp current affecting the luminous flux, J_{rm} is the measured electrical current of the reference lamp, J_{rs} is the required electrical current value to operate the reference lamp (A), J_{cm} is the measured electrical current of the DUT, J_{rs} is the required electrical current value to operate the DUT (A), P_{nl} is the non-linearity error of the photometer head, P_t is the temperature effect on the responsivity of the photometer head and G_a is the geometric alignment error of the lamp holder and photometer screening.

A calibrated PhotoResearch PR-650 SpectraColorimeter, which is traceable to a variable blackbody of the Radiation Temperature Laboratory of TUBITAK UME, was used to measure the color temperature of each of the lamp at the operation position of the lamp (lamp axis (cap up) was vertical).

3.6. Reporting of the Results

Luminous Flux Results performed at TUBITAK UME:

Average values finally obtained by TUBITAK UME for luminous flux of the comparison transfer standard lamps are presented in Table 2 (more details are given in the appendix).

Table 2. Luminous flux of the transfer standard lamps reported by TUBITAK UME

Lamp No.	**Lamp current I, A**	**Luminous flux Φ, lm**	
		Before	**After**
352	1.8950	1884	1884
353	1.9181	1979	1975
355	1.9202	2034	2036
250	1.9530	2552	2555

3.7 Uncertainty of TUBITAK UME Measurements

Table 3 shows the uncertainty budget in measurements of luminous flux al TUBITAK UME.

Table 3. Uncertainty Budget of TUBITAK UME for the Determination of Luminous Flux

Source of uncertainty	Standard uncertainty (%)
luminous flux of the reference lamp, Φ_r	0.52
drift of the value of the reference lamp, $\delta\Phi_r$	0.10
mean of photocurrent reading while measured DUT, y_c	0.018
mean of photocurrent reading while measured the reference lamp, y_r	0.018
mean of photocurrent reading while measured self-absorption factor of the sphere with the reference lamp, y_{ar}	0.021
mean of photocurrent reading while measured self-absorption factor of the sphere with the DUT, y_{ac}	0.021
color temperature of the DUT, T_c	0.22
color temperature of the reference lamp, T_r	0.22
Mismatch index of the sphere photometer, m_s	0.05
electrical current measurement of the reference lamp, J_{rm}	0.011
electrical current measurement of the DUT, J_{cm}	0.013
exponent for changes of the lamp current affecting the luminous flux, m_i	0.15
non-linearity of the sphere photometer, P_{nl}	0.015
temperature effect on the responsivity of the sphere photometer, P_t	0.015
geometric alignment of the lamp holder and photometer screening, G_a	0.10
Combined standard uncertainty (k=1)	0.65
Combined expanded uncertainty (k=2)	1.29

4. MEASUREMENTS AT IO-CSIC

For the bilateral comparison EURAMET.PR-K4.3, IO-CSIC used the same standard luminous flux facility that was used during CCPR-K4 [8]. The luminous flux measurements were carried out using a 3 m in diameter integrating sphere, by direct substitution with standard lamps. The integrating sphere is equipped with a V(λ)-corrected, cosine corrected photometer, a baffle screen, an auxiliary lamp and a temperature sensor.

A baffle of 11 cm in diameter is set to a distance of about 1/6 of the sphere diameter from the detector. The integrating sphere is also equipped with an auxiliary lamp (60 W, tungsten) on the sphere wall. It is used to measure the self-absorption effects of a lamp in the sphere. A temperature sensor is mounted at the back side of the baffle, and the air temperature inside the sphere during measurements is monitored.

Since CCPR-K4 the KCRV has been maintained at IO-CSIC by means of a group of luminous flux standard lamps. The lamps were compared to each other at least once a year. These measurements allowed to estimate an uncertainty $u_{CSIC,st}$ associated with stability of IO-CSIC scale between CCPR-K4 and EURAMET.PR-K4.3:

$$u_{IO-CSIC,st} = 0.28\%$$

At IO-CSIC, the lamps were calibrated by substitution method as comparison with 3 standard lamps. The three lamps are a part of a larger batch of lamps maintaining the luminous flux unit realized at IO-CSIC. These three lamps have been used in the CCPR-K4 comparison.

The results of IO-CSIC measurements of luminous flux for the EURAMET.PR-K4.3 comparison lamps are presented in Table 4 (more details are given in the appendix).

Table 4. IO-CSIC measurements results at EURAMET.PR-K4.3 comparison lamps

Lamp No.	Lamp current I, A	Luminous flux $\Phi_{IO\text{-}CSIC}$, lm
352	1.8950	1884
353	1.9181	1971
355	1.9202	2030
250	1.9530	2550

Total random uncertainty of IO-CSIC measurement during the EURAMET.PR-K4.3 comparison consists of the following components: reproducibility of the independent measurements, instability of lamp power supply and self absorption correction. Same facility was used during CCPR-K4, then we assume that the random uncertainty was the same during both comparisons. Budget of the random uncertainty is presented in Table 5.

The measurements at IO-CSIC were carried out at room temperature of (23.0 ± 1.0)°C and humidity of (35.0 ±5.0) % hr.

Table 5. Budget of random uncertainty (uncorrelated effects) of IO-CSIC measurements during CCPR-K4 and EURAMET.PR-K4.3.

Source of uncertainty	Relative standard uncertainty of luminous flux, %
Repeatability of independent measurements	0.02
Power supply instability	0.03
Self absorption correction	0.02
Total random uncertainty $U_{IO\text{-}CSIC,\,r}$	**0.041**

5. LINK TO THE CCPR KCRV

5.1 Summary of Measurement Results

The luminous flux values measured by both participants are summarized in Table 6.

Table 6. The results of measurements of the luminous flux of all four lamps

Lamp serial number	Current I, A	Luminous flux, lm		
		TUBITAK UME before $\Phi_{TUBITAK\ UME,i}$	TUBITAK UME after $\Phi_{TUBITAK\ UME,i}$	IO-CSIC $\Phi_{IO\text{-}CSIC,i}$
352	1.8950	1884	1884	1884
353	1.9181	1979	1975	1971
355	1.9202	2034	2036	2030
250	1.9530	2552	2555	2550

5.2 Degree of Equivalence of TUBITAK UME

Unilateral Degree of Equivalence (DoE) was evaluated in accordance with the equation (2) of the "Guide for CCPR and RMO Bilateral Key Comparisons (CCPR-G5) [3]

$$D_{TUBITAK\ UME} = D_{IO-CSIC} + {}^{y_{UME}}/_{y_{IO-CSIC}} - 1$$

Where

- $D_{TUBITAK\ UME}$ is the unilateral DoE for TUBITAK UME
- $D_{IO\text{-}CSIC}$ = -0.43% is the unilateral DoE for IO-CSIC, calculated during the CCPR-K4 [5]
- ${}^{y_{UME}}/_{y_{IO-CSIC}} - 1 = \bar{\Delta}$ is the average value of the ratio between the TUBITAK UME average result and the IO-CSIC average result for the 4 lamps that have circulated in this bilateral comparison, subtracting unity to obtain DoE.

The mean values and the relative differences are presented in Table 7.

Table 7. Results of the comparison between TUBITAK UME values and IO-CSIC values.

Lamp Serial number	**Current I, A**	**Luminous flux, lm**		**Relative difference**
		TUBITAK UME $\Phi_{TUBITAK\ UME}$	**IO-CSIC** $\Phi_{IO\text{-}CSIC,i}$	
352	1.8950	1883.9	1884	-0.00004
353	1.9181	1977.1	1971	0.00310
355	1.9202	2035.4	2030	0.00265
250	1.9530	2553.5	2550	0.00138
			Mean difference $\bar{\Delta}$ =	**0.00177**

then

$$D_{TUBITAK\ UME} = -0.43\% + 0.18\% = -0.25\%$$

5.3. Uncertainty of DoE

The uncertainty on the unilateral degree of equivalence of TUBITAK UME is given by

$$u^2(D_{\text{TUBITAK UME}}) = u^2_{\text{TUBITAK UME}} + \underbrace{u^2(x_{\text{ref}})}_{\text{CCPR-K4}} + \underbrace{u^2_{\text{link}}}_{\text{linking quality}} + \underbrace{u^2_{BC}}_{\text{Bilateral Comparison}}$$

Where

1) $u_{\text{TUBITAK UME}}$ is the total standard uncertainty of the non-link laboratory (TUBITAK UME) for a single artifact. This includes uncertainties due to both correlated and uncorrelated effects. According to the uncertainty budget given in the Section 3.7

$$u_{\text{TUBITAK UME}} = 0.65\%$$

2) $u(x_{\text{ref}})$ is the relative standard uncertainty associated with the Key Comparison Reference Value ($u(x_{\text{ref}})$ = 0.1% see KCDB on BIPM website).

3) The third contribution considers the quality of the link provided by the link laboratory

$$u_{\text{link}}^2 = u_{\text{IO-CSIC,st}}^2 + u_{\text{IO-CSIC,KC}}^2 + u_{\text{IO-CSIC,BC}}^2$$

It includes

- The standard uncertainty associated with stability (reproducibility) of the link laboratory's scale between the KC and BC, $u_{\text{IO-CSIC,st}}$
- The standard uncertainty associated with uncorrelated effects (random uncertainty) of the link laboratory during the KC, $u_{\text{IO-CSIC,KC}}$
- The standard uncertainty associated with uncorrelated effects (random uncertainty) of the link laboratory during the BC, $u_{\text{IO-CSIC,BC}}$

These three components were analyzed in the section 4 and estimated as 0.28%, 0.041% and 0.041% respectively.

4) The last contribution u_{BC} (in CCPR-G5 it's represented by the symbol s_{BC}) is the bilateral comparison effect. The only effect that we can consider as BC effect is instability of the artifact. We estimated the standard uncertainty associated with the lamps instability as the maximum drift of all four lamps (Table 6). Therefore:

$$u_{BC} = 0.31\ \%$$

Combining all estimated components, we can calculate the target uncertainty:

$$u(D_{TUBITAK\ UME}) = \sqrt{0.65^2 + 0.1^2 + 0.28^2 + 0.041^2 + 0.041^2 + 0.31^2} = 0.78\%$$

In expanded uncertainty of $D_{TUBITAK\ UME}$:

$$U(D_{TUBITAK\ UME}) = 2u(D_{TUBITAK\ UME}) = 1.6\%$$

6. SUMMARY OF COMPARISON RESULTS

The determined degree of equivalence of TUBITAK UME, $D_{TUBITAK\ UME}$, and its associated expanded uncertainty are summarized in Table 8.

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Table 8. Degree of equivalence(DoE) of TUBITAK UME" and associated expanded uncertainty

DoE of TUBITAK UME $D_{TUBITAK\ UME}$	-0.25%
Expanded uncertainty (*k*= 2) $U(D_{TUBITAK\ UME})$	1.6%

7. LITERATURE

[1] Guidelines for CIPM key comparisons, 1 March 1999
[2] Guide No.3, Euramet Guidelines on Conducting Comparisons Ver 02.7 (2002)
[3] Guidelines for CCPR «Guidelines for CCPR and RMO Bilateral Key Comparisons»(CCPR-G5, October 10th, 2014).
[4] Guidelines for RMO PR Key Comparisons (CCPR-G6 Version 1.0, 10 October 2014)

[5] CCPR-K4 report, http://kcdb.bipm.org/appendixB/appbresults/ccpr-k4/ccpr-k4.pdf.
[6] BIPM database: http://kcdb.bipm.org/appendixB/appbresults/EURAMET.PR-K3.a/EURAMET.PR-K3.a_Technical_Protocol.pdf
[7] Samedov F., Durak M. “Realization of luminous flux unit of Lumen at UME”, Optica Applicata, 34(2), 265-274, 2004.
[8] G. Sauter, D. Lindner and M. Lindemann CCPR, Key Comparison K3a of Luminous Intensity and K4 of Luminous Flux with Lamps as Transfer Standards, PTB-Opt-62, ISBN 3-89701-471-8PR.

A. APPENDIX

A.1. Detailed measurements results

A.1.1 Measurements results at TUBITAK UME (round 1)

Lamp S. No	Current *I (A) ± U(A)*	Voltage *U (V) ± U(V)*	Luminous Flux *Φ (lm) ± U(lm)*	Correlated Color Temperature *T (K) ± U(K)*
352	1.8950 ± 0.0001	86.97 ± 0.01	1886	2715
			1881	2715
			1885	2715
		average	**1884 ± 24**	**2715 ± 12**
353	1.9181 ± 0.0001	87.58 ± 0.01	1981	2715
			1977	2716
			1978	2715
		average	**1979 ± 25**	**2715 ± 12**
355	1.9202 ± 0.0001	89.57 ± 0.01	2032	2715
			2037	2715
			2032	2715
		average	**2034 ± 26**	**2715 ± 12**
250	1.9530 ± 0.0001	95.59 ± 0.01	2548	2715
			2553	2714
			2555	2715
		average	**2552 ± 33**	**2715 ± 12**

A.1.2 Measurements results at IO-CSIC

Table of luminous flux of the test lamps (lm)

Standard lamp ⟹ **Test lamp ⇓**		**PF97A (lm)**	**PF97B (lm)**	**PF97C (lm)**	**Mean value (lm)**	**Relative std. deviation**
352	series 1	1885	1883	1883		
	series 2	1887	1884,5	1884,5		
	series 3	1888	1882	1883		
	Average	**1887 ± 32**	**1883 ± 32**	**1884 ± 32**	**1884 ± 32**	**3.522E-04**
353	series 1	1973	1975	1967		
	series 2	1974	1976	1970		
	series 3	1973	1967	1967		
	average	**1973 ± 33**	**1973 ± 33**	**1968 ± 33**	**1971 ± 33**	**6.155E-04**
355	series 1	2032	2029	2026		
	series 2	2034	2033	2033		
	series 3	2032	2028	2027		

	average	**2032.7 ± 34**	**2030 ± 34**	**2030 ± 34**	**2030 ± 34**	**4.864E-04**
250	series 1	2552	2550	2546		
	series 2	2554,2	2554,9	2552		
	series 3	2554	2545	2546		
	average	**2553.4 ± 43**	**2550 ± 43**	**2549 ± 43**	**2550 ± 43**	**5.078E-04**

Table of voltages, currents and correlated color temperature of the test lamps (V)

Lamp		**Current (A)**	**Voltage (V)**	**Correlated color temperature (K)**
352	series 1	1.8951	86.24	
	series 2	1.8950	86.19	
	series 3	1.8950	86.20	
	Mean values	1.8950	86.21	2715
	Rel.std.deviation	1.759E-05	1.507E-04	0
353	series 1	1.9181	87.80	
	series 2	1.9181	87.77	
	series 3	1.9180	87.72	
	Mean values	1.9181	87.76	2715
	Rel.std.deviation	1.738E-05	2.659E-04	0
355	series 1	1.9201	89.71	
	series 2	1.9202	89.72	
	series 3	1.9202	89.71	
	Mean values	1.9202	89.71	2715
	Rel.std.deviation	1.736E-05	3.715E-05	0
250	series 1	1.9530	95.82	
	series 2	1.9531	95.79	
	series 3	1.9530	95.77	
	Mean values	1.9530	95.79	2715
	Rel.std.deviation	1,707E-05	1.517E-04	0

A.1.3. Measurements results at TUBITAK UME (round 2)

Lamp **S. No**	**Current** ***I (A) ± U(A)***	**Voltage** ***U (V) ± U(V)***	**Luminous Flux** ***Φ (lm) ± U(lm)***	**Correlated Color Temperature** ***T (K) ± U(K)***
352	1.8950 ± 0.0001	86.97 ± 0.01	1883	2715
			1888	2716
			1882	2715
		average	**1884 ± 24**	**2715 ± 12**
353	1.9181 ± 0.0001	87.58 ± 0.01	1974	2715
			1977	2715
			1975	2715

		average	**1975 ± 25**	**2715 ± 12**
355	1.9202 ± 0.0001	89.57 ± 0.01	2033	2715
			2037	2714
			2039	2715
		average	**2036 ± 26**	**2715 ± 12**
250	1.9530 ± 0.0001	95.59 ± 0.01	2558	2715
			2555	2715
			2552	2715
		average	**2555 ± 33**	**2715 ± 12**