EURAMET.PR-K4.2

(EURAMET Project 1344)

Final report

Bilateral comparison of luminous flux using lamps as transfer standards

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Preamble

The EURAMET project 1344, “Comparison of luminous flux using lamps as transfer standards” between LNE-CNAM, France and RCM LIPI, Indonesia was intended to link the RCM LIPI realized lumen to the CCPR key comparison reference values and to demonstrate the RCM LIPI calibration measurement capability in calibrating tungsten standard lamps for transferring this unit.

A technical protocol for this comparison was agreed upon by the participants and submitted to the EURAMET and to the CCPR for approval. The comparison was registered on BIPM key comparison data base with the number EURAMET.PR-K4.2.

Introduction

The Laboratoire National de Métrologie et d'Essais, LNE-CNAM (France) and The National Institute of Metrology, RCM LIPI (Indonesia) agreed in December 2013 to conduct a bilateral comparison on luminous flux using a group of lamps as transfer standards.

The aims of the comparison were :

- To link the RCM LIPI realized lumen to the CCPR K4 reference value [1]
- To demonstrate the RCM LIPI capability in calibrating tungsten standards lamps.

A technical protocol following the guidelines established by the BIPM and taking into account of the technical protocol of the key comparison of luminous flux organized by the CIPM was agreed upon.

The comparison and its protocol were approved by the CCPR and registered with KCDB with the comparison number : EURAMET.PR-K4.2.

1 Organization

The comparison was organized and conducted within the EURAMET Project 1344.

1.1 Participants

Address	Person in charge	Contact
Laboratoire National de Metrologie d`Essais LNE-CNAM / CNAM 61 Rue du Landy 93210 La Plaine Saint Denis France	Gaël Obein	Tel : +33 1 58 80 87 88 Fax : +33 1 58 80 89 00 e-mail: gael.obein@cnam.fr.
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TABLE 1 : LIST OF PARTICIPANTS

The LNE-CNAM (France) acted as the pilot laboratory.

1.2 Form of comparison

The comparison was carried out by successive calibrations of a group of travelling standard lamps in the two laboratories. Details on the transfer standards are given in section 3 of this report.

The lamps were first calibrated by RCM LIPI. Then they were hand carried to LNE-CNAM where a second calibration was performed. After being carried back to RCM LIPI, the lamps were calibrated again in order to check for the drift.

1.3 Duration

The measurements were performed over the period May 2014 to October 2014.

2 Description of the artefacts

The lamps used in the comparison were three lamps, manufacturer OSRAM/GEC, 100V 100W with clear bulbs, serial numbers #364, #388 and #389. These lamps were provided by RCM LIPI. The lamps were operated at a colour temperature Tc = 2800 ± 30 K. The electrical parameters are given in **Table 2.**

Table 2 – Electrical parameters of the standard lamps used for the comparison

Lamp serial	Current (A)	dc voltage (May 2014) (V)	dc voltage (October 2014) (V)
364	1,0700	98.50	98.60
388	1,1000	98.70	98.99
389	1,1000	95.64	95.60

2.1 Transport and handling

The lamps were hand carried from one laboratory to the other. After each transportation the lamps were thoroughly inspected and the electrical parameters were checked. There was no reported damage of the transfer lamps during the transportations.

3 Measurement conditions

3.1 Laboratories environment

LNE-CNAM performed the measurements at a temperature of (18 +/-1) °C and a relative humidity of (50+/-10) %.

RCM LIPI performed the measurements at a temperature of (23 +/-3) °C and a relative humidity of (50+/-10) %.

3.2 Lamp operation details

In order to avoid premature ageing, the lamps were operated at a colour temperature of 2800 K. The lamps were operated in a vertical position, cap up. For all lamps, the negative voltage was applied to the central connector (figure 1). Four wires device for measurements of the electrical parameters (current and voltage) were used throughout.

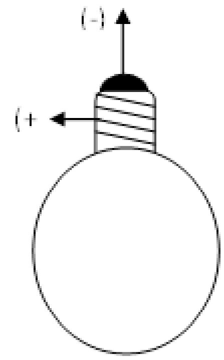


Figure 1. Electrical poles of the lamps

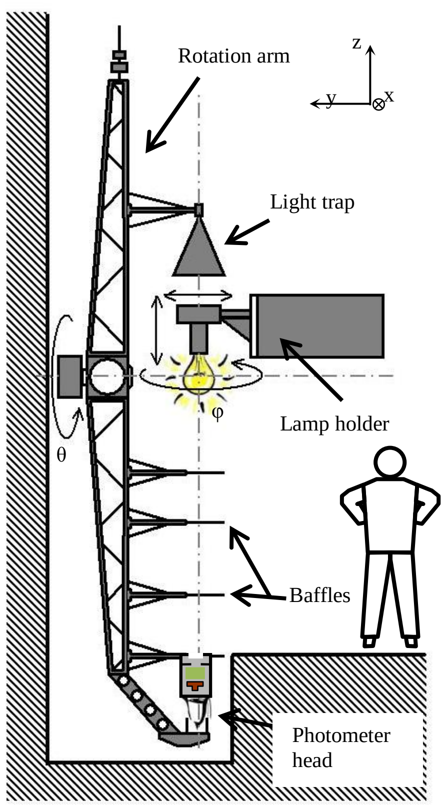
3.3 **Mesurande**

The mesurande was the total luminous flux of the lamps, as obtained by spherical integration of the luminous intensity or illuminance.

3.4 **Measuring conditions.**

At LNE-CNAM.

The measurements are carried out on our reference facility which is 7 meters diameter “homemade” goniophotometer (figure 2).



The lamp is operated vertical, cap up. The goniophotometer realises the spatial measurement of the luminous intensity according to the following method: the lamp is rotated around its vertical axis over a full circle (360°). The photometer rotates in a vertical plane containing the axis of the lamp. Its rotation is only a half of a circle (180°). The lamp is put at the center of the circle described by the photometer. These two rotations allow measuring the luminous intensity distribution of the lamp all over the space around it.

Figure 2: general view of the goniophotometer.: the lamp holder allows the alignment and the rotation of the lamp. The photometer rotates thanks to the rotation arm. 4 baffles and a light trap are used to reduce the stray light. The man is 1.80m.

The main characteristics of the facility are:

- Distance between source and detector : 3 400 mm
- Photometer cosine corrected, diameter : 60 mm (angular measurement 1°)
- Mosaic V(λ) filter temperature controlled within ± 0.1°C
- Speed of motion of the detector : 4°/s
- Standard uncertainty on the angular setting : 0.02°

For the measurement, the lamp is set at an azimuth angle and the photometer is moved on half a circle, taking a measurement every 3°. Then the lamp is rotated by an angle of 6° and the motion of the photometer starts again in the reverse direction. The measurement continues until all the sphere has been described giving a total number of 3 600 luminous intensity data and the same number of angle data.

In order to keep the time of measurement at a reasonable level (about 2 hours) the measurements are taken “on the fly”.

The luminous flux emitted by the lamp is calculated by integrating the luminous intensity distribution over the complete sphere.

The photoelectric current is measured using a high quality current to voltage converter with a gain of 10^6 and a high precision voltmeter. 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 ppm.

The motorization of the rotation of the lamp and of the photometer is done by stepping motors connected with step down gears free from play. With stepping motors it is possible to have, with the same electronic device, the motor rotation and the angular positioning by pulse counting measurements. The data regarding the luminous intensity and the angle are taken at the same time.

At RCM LIPI

The measurement is carried out on KIM-LIPI using LMT goniophotometer, with 3.4 meters in diameter (figure 3).

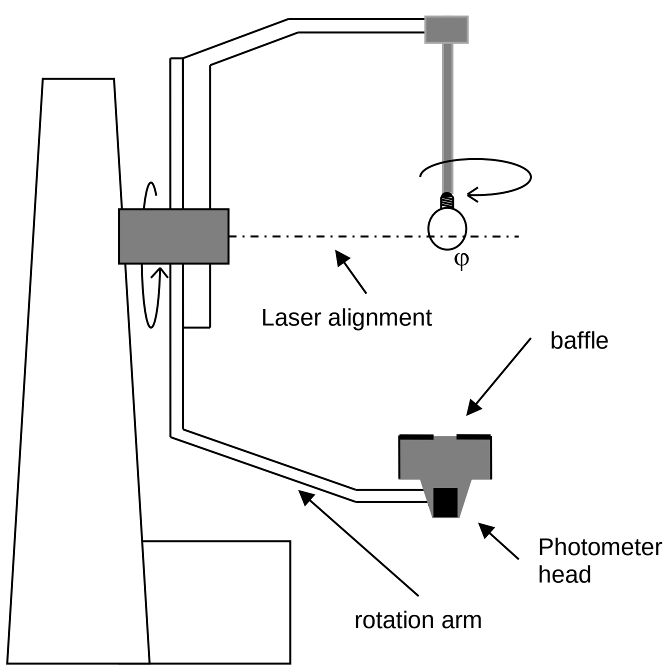


Figure 3 : general setup of goniophotometer.

The lamp operated vertical, cap up. The lamp positioned in the center of the rotation arm circle using laser, pointed to the filament of the lamp. The DC current is monitored using Digital power meter, Yokogawa WT-2010. The pole of the lamps can be seen in the figure 3.

The lamp rotates around 360° in the C plane, and the arm with photometer head rotates in 180° starting from under the lamp.

Characteristics of this goniophotometer are:

- Distance between source and detector is 1719 mm.
- Photometer cosine corrected, diameter 30.0 mm (spatial evaluation cos-correction up to 30°).
- V(λ) mismatch : 0.6%
- Temperature of the photometer element is thermostatically stabilized with an accuracy of ± 0.1°C.
- Speed of motion : 5°/s

Measurements are taken with rotation arm under the lamp moving half of circle (180°) to the top.

Measurement data are taken every 1° step.

The photo electric current is measured using LMT S 1000 with reading from 0.0001 – 80000 lux.

4 Analysis of the measurement results

4.1 RCM LIPI results summary

The measurements at RCM LIPI were carried-out in May 2014 for the first round and in October 2014 for the second round. The results are summarised in **Table 3**.

Table 3 – Results of the measurements at RCM LIPI

Lamp serial number	Luminous flux (lm)		Standard deviation (%)	Standard uncertainty (%)
364	Round 1	1035.7	0.08	0.61
	Round 2	1037.7	0.24	0.61
	Mean	1036.7	0.25	0.61
388	Round 1	1187.5	0.25	0.61
	Round 2	1189.8	0.10	0.61
	Mean	1188.7	0.27	0.61
389	Round 1	1117.7	0.05	0.61
	Round 2	1120.2	0.17	0.61
	Mean	1119.0	0.17	0.61
		Averaged rel. std. dev.	0.23	0.61

The value of RCM LIPI measurements assigned to one lamp is the mean of the measurements of the two rounds. The relative standard deviation of this mean value listed in the lines denoted with “mean” is determined as the square root of the sum of squares of the standard deviations of each round. The average of these means is denoted as “averaged rel. std. dev.” with the number 0.48% and is stated in the last line of table 3. This relative standard deviation is uncorrelated and mainly originated in the alignment and stability of the standard lamps. It is a significant contribution to the estimated constant relative uncertainty of 0.61% for the relative standard uncertainty in the last column. The square root of the difference of the squares of these two numbers $\left(0.56 = \sqrt{0.61^2 - 0.23^2}\right)\%$ is the part in the combined uncertainty common to each measurement creating correlation.

4.2 LNE-CNAM results summary

The measurements at LNE-CNAM were carried-out in August 2014. The results are summarised in **Table 4**.

Table 4 Results of the measurements at LNE-CNAM

Lamp serial number	Luminous flux (lm)	Standard deviation (%)	Standard uncertainty (%)
364	1043.0	0.038	0.53
388	1196.9	0.017	0.53
389	1125.4	0.009	0.53
	Averaged rel. std. dev.	0.021	0.53

4.3 Comparison of results

The results of the two laboratories were compared by calculating the relative difference of the luminous flux values assigned by each participant to a lamp using the following formula:

$$\Delta_i = \frac{\Phi_{\alpha,i} - \Phi_i}{\Phi_i} = \frac{\Phi_{\alpha,i}}{\Phi_i} - 1 \tag{1}$$

Where

Δ_i is the relative difference for the i^{th} lamp

$\Phi_{\alpha,i}$ is the luminous flux value of the i^{th} lamp assigned by RCM LIPI

Φ_i is the luminous flux value of the i^{th} lamp assigned by LNE-CNAM

The average relative difference for the comparison can be determined as:

$$\overline{\Delta} = \frac{1}{n}\sum_{i=1}^{n}\Delta_i \quad (2)$$

The unilateral Degree of Equivalence (DoE) of the non-link laboratory RCM LIPI is calculated from the unilateral DoE of the link laboratory LNE-CNAM in the KC and the difference between the measurement results of RCM LIPI and LNE-CNAM

$$D_{\propto} = X/X_{ref} - 1 + (Y_{\propto}/Y - 1) = X/X_{ref} - 1 + \bar{\Delta} \quad (3)$$

Where

D_α is the unilateral DoE of RCM LIPI

$D=x / x_{ref} - 1$ is the unilateral DoE for LNE-CNAM, calculated during the KC from the measurement result x and KCRV x_{ref} .

$Y_\alpha / Y - 1 = \overline{\Delta}$ is the “average value” (of multiple artefacts) of the ratio between RCM LIPI measurement result (or average of RCM LIPI measurements) and the LNE-CNAM measurement result (or average result) for each artefact in the comparison, subtracting unity to obtain a DoE.

The uncertainty component of the unilateral DoE is given as an expanded uncertainty

$$U(D_\alpha) = 2u(D_\alpha) \quad (4)$$

where the standard $u^2(D_\alpha)$ uncertainty is calculated using

$$u^2(D_{\propto}) = u_{rel}(unit)^2 + u_{rel}(transfer)^2 + u_{rel}(pilot)^2 + u_{rel}(homog)^2 \quad (5)$$

There are four contributions in this uncertainty calculation:

- The realization, including the maintenance since that time u_{rel}(unit) ,
- The transfer of the maintained unit at the pilot laboratory u_{rel}(transfer),
- The stability or repeatability of measurements at the pilot laboratory u_{rel}(pilot),
- The homogeneity of a batch of lamps of a participant u_{rel}(homog.).

According to equations (2), (3) and (5) the final results of the measurements performed at RCM LIPI and LNE-CNAM and the results of the comparison are given in table 5 and figure 4.

Table 5 – Results of the comparison between RCM LIPI values and LNE-CNAM values.

Lamp	RCM LIPI (lm)	LNE-CNAM (lm)	Relative difference
364	1036,7	1043,0	-0,0060
388	1188,7	1196,9	-0,0069
389	1119,0	1125,4	-0,0057
		Mean difference	**-0,0062**
		DoE LNE-INM	0,0069
		DoE RCM LIPI	**0,0007**
Contributions to DoE standard uncertainty		u_{rel} *(unit)*	0,0061
		u_{rel} *(transfer)*	0,0021
		u_{rel}(pilot)	0,00045
		u_{rel}(homog.)	0,0010
RCM LIPI unilateral DoE standard uncertainty		$u^2(D_\alpha)$	0,0065
RCM LIPI unilateral DoE expanded uncertainty		$U(D_\alpha)=2u(D_\alpha)$	**0,013**

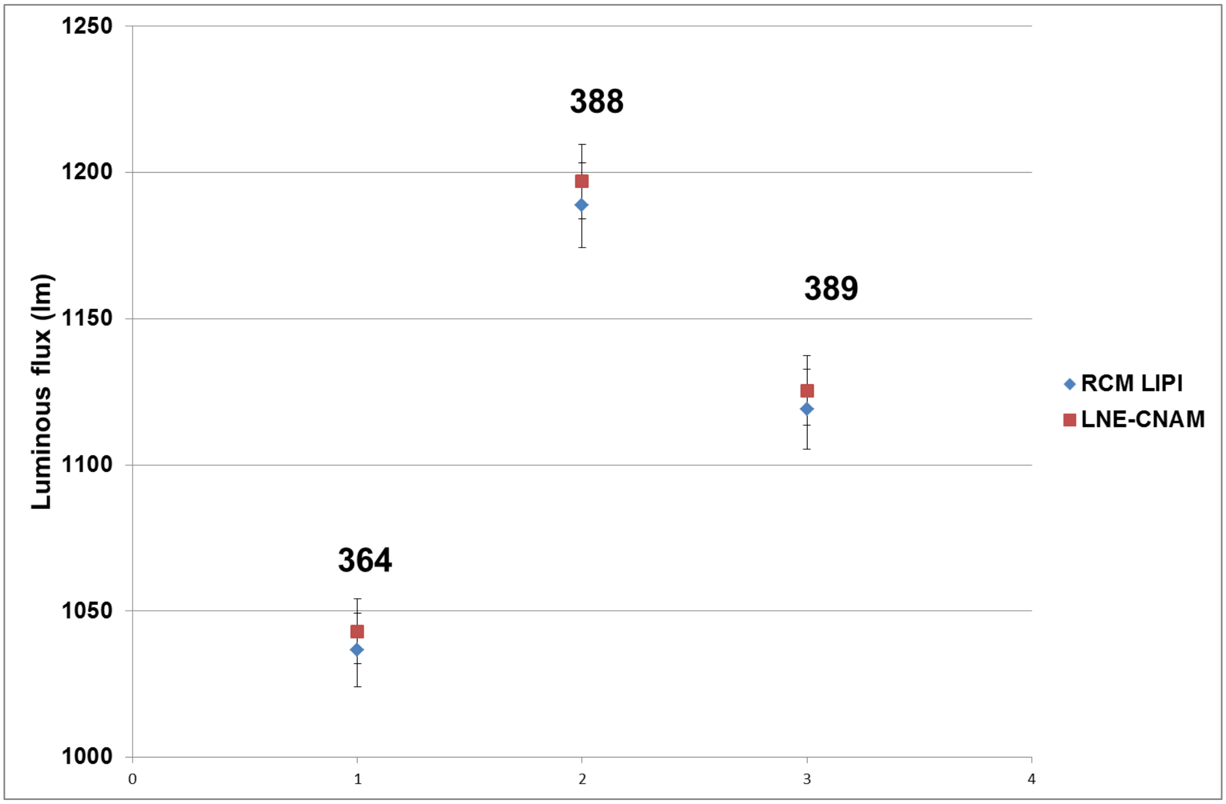


FIGURE 4: Results of the comparison between RCM LIPI values and LNE-CNAM values.

4.4 Comments:

The result in table 5 shows an average difference $\overline{\Delta} = -0.62\%$ between the calibrations carried out at RCM LIPI and at LNE-CNAM, which indicates a good agreement between the results of the two laboratories taking into account the expanded uncertainties of 1.22% and 1.06% for RCM LIPI and LNE-CNAM respectively.

The unilateral DoE of RCM LIPI with respect to the CCPR-K4 KCRV is 0.0007 with an expanded uncertainty of 0.013.

5 Measurement uncertainties

5.1 General

The measurement uncertainties were estimated according to the ISO Guide to the Expression of Uncertainty in Measurement.

5.2 LNE-CNAM traceability and measurement uncertainty

The photometer is calibrated using a set of three luminous intensity transfer standard lamps of the laboratory. The photometer is calibrated just before and after each measurement campaign. The luminous intensity lamps are mounted on the goniophotometer allowing an “in situ” calibration of the photometer. The sensitivity of the photometer is expressed in $V \cdot cd^{-1}$ and takes into account the current to voltage converter.

The set of transfer standard lamps is periodically compared with another set of transfer standard lamps that has participated to CCPR-K3a key comparison and has a traceability to the realization of the candela carried out in 1984 (see CCPR-K3a report for details).

We integrate the luminous intensity of the lamp on the full sphere to compute the luminous flux of the lamps.

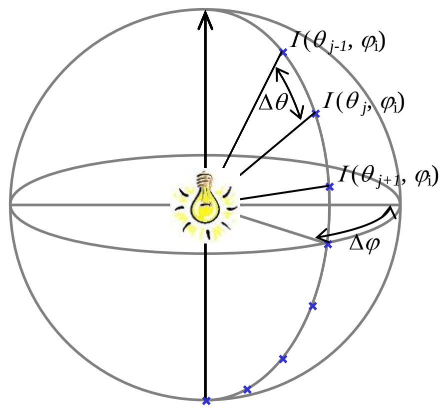


Figure 2: Angular notations. θ is the elevation angle and varies between 90° and -90°. φ is the azimuth angle. $I(\theta_j\ \varphi_i)$ is the luminous intensity at the position $(\theta_j\ \varphi_i)$. For a luminous flux measurement, the steps are $\Delta\theta$ = 3° and $\Delta\varphi$ = 6° which gives 3600 luminous intensity measurements

According to the notations described on figure 2, the measurement model is given by:

$$\phi = \frac{1}{S} \cdot \sum_i \sum_j y_{ij} \cdot \cos\theta_j \cdot \Delta\varphi \cdot \Delta\theta \cdot corr \tag{6}$$

$$corr = \left(1 - \frac{y_0}{y_{ij}} - mI \cdot \Delta J\right) \tag{7}$$

Were Φ is the luminous flux of the lamp
corr is a correction factor with about unity value.
S is the responsivity of the photometer
y_{ij} is the voltage at the photometer at the angular position (θ_j ; φ_i) and corrected for straylight and offset y_0 .
mI = 6.75 is the coefficient for corrections of relative lamp current differences
ΔJ is the relative difference in the lamp current setting.

The lamps run at a colour temperature of (2800 ± 30) K, the same colour temperature as the luminous intensity transfer standards lamps. The photometer head of the photometer is very well *V*(λ) corrected. No correction and no uncertainty are applied for the spectral matching factor of the photometer head.
The other contributions to the combined uncertainty are summarised in **Table 6.**

Table 6 – uncertainty budget of LNE-CNAM for luminous flux of lamp.

Source	Symbol	Probability distribution.	Divisor	100 × Rel. Standard uncertainty
Sensitivity of the photometer	S	Normal	1	0.45
Voltage measurement for 1 position	y_{ij}	Normal	1	0.001
Voltage measurement for straylight	y_0	Normal	1	0.001
Azimuth step	$\Delta\varphi$	Rectangular	√3	0.002
Elevation step	$\Delta\theta$	Rectangular	√3	0.003
Misalignment lamp	ε			
x		Rectangular	√3	0.001
y		Rectangular	√3	0.001
z		Rectangular	√3	0.001
Current in the lamp	ΔJ	Normal	1	0.006
Aging of the standard lamp	$\gamma \cdot \Delta t$	Rectangular	√3	0.01
Standard deviation		Normal	1	0.10
Combined uncertainty		Normal		0.53
Expanded uncertainty		Normal (k=2)		1.06

5.3 RCM LIPI traceability and measurement uncertainty

The photometer is calibrated using luminous intensity lamp which is traceable to A*STAR Singapore. The photometer calibrated every 4 years, this calibration is done in the photometric bench. The distance between luminous intensity lamp and photometer head is 1.72 m, the sensitivity of the photometer expressed in A/lux. The luminous intensity standard lamps are calibrated every 5 years.

The luminous flux of light source is defined as:

$$\Phi = \int_{A_2} E \, dA_2 \tag{8}$$

With

A_2 an enveloping surface enclosing the light source (envelope)

E iiluminance on the area element dA_2

If $(r,\ \vartheta, \varphi)$ are polar coordinates of a coordinate system connected to the goniophotometer $(0 \leq \vartheta \leq \pi, 0 \leq \varphi \leq 2\pi)$, the enveloping surface (virtual sphere, radius r) can be divided into m zones $m \geq 60$ of equal width $\Delta\vartheta = \pi/m$. With $\vartheta_i = i.\Delta\vartheta$ the integral in the above formula can be replaced for evaluation of the luminous flux by:

$$\Phi = 2\pi^2 \sum_{i=1}^{m} \bar{E}_i [cos\vartheta_{i-1} - cos\vartheta_i] \tag{9}$$

With

Φ luminous flux

r radius of goniophotometer

$\bar{E}_i$ mean value of illuminance of zone *I*

ϑ_i angle to bottom border of zone *i*

The uncertainty budget is summarised in **Table 7**.

No	Components (Xi)	Unit	Distribution	Ui	divisor		Coeff. Sensitivity (Ci)		Contribution Ci . Ui
1	Repeatability	%	Normal	0.048	1		1		0.25
2	Resolution	%	Rectangular	0.005	1.73		1		0.003
3	Photometer C	%	Normal	0.84	2		1		0.42
4	Alignment	%	Rectangular	0.1	1.73		1		0.058
5	Temperature	%	Rectangular	0.01	1.73		1		0.006
6	Current settin	%	Normal	0.01	2		6.2		0.031
7	Distance	%	Normal	0.08	2		2		0.08
8	Angle accura	%	Rectangular	0.224	1.73		1		0.129
9	Photometer L	%	Rectangular	0.2	1.73		1		0.116
10	Geometric of	%	Rectangular	0.232	1.73		1		0.134
11	Mounting lam	%	Rectangular	0.477	1.73		1		0.276
Combination uncertainty									0.61
Coverage factor									2
Expanded uncertainty									1.22

Table 7 – uncertainty budget of RCM LIPI for luminous flux of lamp.

6 References

[1] Guide to the Expression of Uncertainty in Measurement (ISO)

[2] EURAMET PR-K4 and EURAMET PR-K3a technical protocol. Approved 2008-06-03

A Appendices

A.1 Analysis of uncertainties

In order to provide the necessary comparability, the uncertainties were estimated and expressed according to ISO-GUM. The main components of the measurement uncertainties were defined as bellow:

A type:
Repeatability of measurements values – the standard deviation of the results obtained in a set of measurements on the artefact, without realignment;

B type
Uncertainty of the reference standard-certified combined standard uncertainty of the reference standard in use;
Uncertainty due to the positioning of the artefact or photometer;
Uncertainty associated to the measurement methods (lamps dc supply, photocurrents values, etc.);

Other relevant components specific to one or the other participant measurement technique.

A2 Detailed measurements results

A2.1 Measurements at RCM LIPI (ROUND I)

Lamp serial number	Luminous flux (lm)	Lamp current (A)	Lamp voltage (V)	Transfer standard deviation (%)	Number of readings	Standard uncertainty (%)	Cumulative burning time (h)
364	1035.7	1.0700	98.58	0.08	3	0.61	2
388	1187.5	1.1000	98.78	0.25	3	0.61	2
389	1117.7	1.1000	95.72	0.05	3	0.61	2

A2.2 Measurements at LNE-CNAM

Lamp serial number	Luminous flux (lm)	Lamp current (A)	Lamp voltage (V)	Transfer standard deviation (%)	Number of readings	Standard uncertainty (%)	Cumulative burning time (h)
364	1043.0	1.0700	98.76	0.038	2	0.56	2.5
388	1196.9	1.1000	99.02	0.017	2	0.56	3
389	1125.4	1.1000	95.78	0.009	2	0.56	3

A2.3 Measurements at RCM LIPI (ROUND II)

Lamp serial number	Luminous flux (lm)	Lamp current (A)	Lamp voltage (V)	Transfer standard deviation (%)	Number of readings	Standard uncertainty (%)	Cumulative burning time (h)
364	1037.7	1.0700	98.68	0.24	5	0.61	3.5
388	1189.8	1.1000	99.07	0.10	5	0.61	3.5
389	1120.2	1.1000	95.68	0.17	5	0.61	3.5