Report of SIM Key Comparison
SIM.PR-K4
Luminous Flux

FINAL REPORT
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1 Introduction

In compliance with the established BIPM politics on comparisons, the SIM Photometry and Radiometry Working Group decided to conduct a key comparison on total luminous flux in order to provide an opportunity for its member National Metrology Institutes (NMIs) that did not participate in the CCPR-K4 Comparison, to get a link to the Reference Value obtained for this quantity (the lumen) and to derive the corresponding Degrees of Equivalence.

This SIM Key Comparison was then labeled as SIM.PR-K4 and the *Centro Nacional de Metrología* (CENAM), the NMI of Mexico, was designated to act as the pilot laboratory. Five laboratories including the pilot laboratory participated in this comparison, two of which provided the link to the reference value obtained as a result of the CCPR-K4 comparison.

The results of these comparisons are the differences of the participating NMIs scales to the CCPR-K4 Luminous Flux Key Comparison Reference Value, calculated apart from the results obtained by NIST and NRC; the NMIs participating in both comparisons.

By fulfilling the CCPR Guidelines for Key Comparisons, CENAM prepared the SIM.PR-K4 technical protocol in accordance with the one used for CCPR-K4, which final version can be consulted from this report in the Annex A, and the comparison followed the “star-type” scheme, using three or four lamps per participant laboratory, as mentioned at Table 1.

2 Participants

Table 1 presents the list of participating NMIs in the SIM.PR-K4 and the lamps used by each participant.

Table 1. SIM.PR-K4 Participant NMIs and lamps used.

Acronym	NMI	Country	Lamps Used
CENAM	*Centro Nacional de Metrología*	Mexico	3 Polaron FL200L 1 Osram Wi40G
INMETRO	*Instituto Nacional de Metrologia, Normalização e Qualidade Industrial*	Brazil	3 Osram Wi40G
INTI	*Instituto Nacional de Tecnología Industrial*	Argentina	3 GEC 200W
NIST	National Institute for Standards and Technology	United States of America	4 Polaron LF200L
NRC	National Research Council	Canada	4 Polaron LF200L

3 Transfer Standards

3.1 Specification of the transfer standard lamps

Three different types of luminous flux standard lamps as shown in Table 1 were used. The lamps were characterized and calibrated by each participant as indicated in section 5. Operating conditions for each lamp are indicated in Table 2. At the pilot lab, current was set as close as possible to the specified current, a contribution to the uncertainty was included in the uncertainty estimation of the pilot.

Table 2. Operating conditions of all lamps, provided by the participants.

Lamp	Current (A)	Voltage (V)
CENAM		
Polaron P270	1,915	110,3
Polaron P466	1,883	105,2
Polaron P484	1,900	105,3
Osram F002	5,557	27,7
INMETRO		
Osram 544	5,503	30,4
Osram 546	5,515	30,5
Osram 627	5,781	30,5
INTI		
Gec 437	1,9300	104,7
Gec 447	1,9300	106,0
Gec 448	1,9300	107,7
NIST		
Polaron TF9-1	1,9500	89,4
Polaron TF9-2	1,9200	90,3
Polaron TF9-3	1,9400	89,3
Polaron TF9-4	1,9400	90,4
NRC		
Polaron P514	1,8993	93,4
Polaron P517	1,9129	91,9
Polaron P518	1,8937	89,5
Polaron P525	1,9293	89,3

3.2 Schedule of measurements

The comparison was conducted according to the time schedule presented in Table 3.

Table 3. SIM.PR-K4 time schedule.

Activity	Date of measurements by CENAM	Date of measurements by participant
CENAM lamps measurement – first round	August, 2004.	
INMETRO lamps measurement	December, 2004.	First round: November, 2004. Second round: June, 2005.
INTI lamps measurement	May, 2005.	First round: April 2005 Second round: August, 2005.
NIST lamps measurement	June, 2005.	First round: March, 2005. Second round: August, 2005.
NRC lamps measurement	October, 2005.	First round: July, 2005.

		Second round: April, 2006.
CENAM lamps measurement – second round	October, 2005.	

4 Measurements at CENAM as the pilot laboratory

The lamps were measured using a 2 m integrating sphere, operated under the following conditions:

- Lamp axis is vertical (cap up)
- 4 pole socket was used at the polarity indicated by each participant
- Lamps were feed at constant current according to the specification given by participant.
- Warm up and stabilization of 10 minutes was allowed for each lamp, before the start of measurements, monitoring the stability of readings during that period.
- Each lamp was operated at least tree times in order to get the measurement results.
- During the comparison, the stability of the CENAM setup was monitored using reference and working standard lamps. The reference lamps allowed us to determine the working lamps aging.

5 Participants' measurement facilities and scales

5.1 CENAM

The lamps used in the comparison are calibrated against reference standards, which have been calibrated by NIST using the absolute integrating sphere method.

The measurement of the lamps was performed using the standard substitution method in a sphere photometer. The sphere photometer is composed of a 2m integrating sphere and a detector mounted at the output port of the sphere. The relative spectral responsivity of the sphere photometer was determined as the product of the relative spectral throughput of the sphere (estimated from the measured spectral reflectance of the coating) times the relative spectral responsivity of the detector.

The integrating sphere used has a diameter of 2 m and is coated internally with a uniform layer of spectrafect™. The flux lamps are mounted in a base-up configuration at the center of this sphere into a lamp socket supported from the top of the sphere. The lamp socket had four electrical leads (2 for lamp current and 2 for the lamp voltage measurement). A circular baffle, also coated with spectraflect™, is suspended on wire supports from the wall of the sphere and was situated approximately halfway between the lamp and the detector port.

5.2 INMETRO

Luminous flux standard lamps used in the comparison are calibrated against Luminous flux reference standard lamps calibrated by BIPM in 1999 using the absolute integrating sphere method.

The measurement method used is based on the substitution method in an integrating sphere of 2 m diameter, with the inside sphere wall painted with a special photometer paint based on barium sulfate. The lamp hold is fixed in pendant burning position in the center of the sphere with lamp socket with four electrical contacts of highest quality, consisted of two contacts for lamp voltage measurement and two for lamp current measurement. The lamps are fixed with base up position, the photometer head used is V(λ) – corrected silicon photodiode with a cosine-corrected angular responsivity and the circular baffle is located at approximately halfway between detector port and the lamp.

5.3 INTI

The lumen is derived from the candela (realized at INTI by absolute radiometry) by a type C goniophotometer, and maintained by a set of 22 standard lamps.

Up to 2003 the lumen was realized using a spiral goniophotometer (Ref: Participation of INTI in CIPM key comparison k3a of luminous intensity and k4 of luminous flux, J. Cogno, http://www.science.oas.org/sim/publications/SIM_2001/parte1.pdf).

The device was replaced by a C-type mirror goniophotometer, nevertheless the mirror is not used for reflecting the light; the device works as a standard C-type goniophotometer. Last realization: 2005-04-29.

5.4 NIST

The NIST lumen was realized by using the 2,5 m absolute integrating sphere, based on the NIST detector-based candela scale (Y. Ohno and Y. Zong, Detector-Based Integrating Sphere Photometry, proceedings, CIE 24th Session – Warsaw'99, pp.155-160). Measurements were made using NIST 2,5 m absolute integrating sphere.

The last realization of the NIST lumen was January, 2005.

5.5 NRC

A total of nine NRC Total Luminous Flux Standard lamps were used to calibrate the Polaron lamps used during this comparison. These standards are linked to the SI through our NRC standards of luminous intensity that were established in 1987. The original linkage between the NRC scale of Total Luminous Flux and the NRC scale of Luminous Intensity was performed in 1953 using a goniophotometer. The uncertainty in this linkage, and the subsequent adjustment of the NRC lumen to correspond with changes in the NRC candela, have been established through NRC participation in the CCPR comparisons of 1957, 1961, 1969 and 1985.

The measurement of the lamps was performed using the standard substitution method in a sphere photometer. The sphere photometer is composed of an integrating sphere and a detector mounted at the output port of the sphere. The relative spectral responsivity of the sphere photometer was determined as the product of the relative spectral throughput of the sphere (estimated from the measured spectral reflectance of the coating) times the relative spectral responsivity of the detector.

The integrating sphere used has a diameter of 3 m and is coated internally with a uniform layer of $BaSO_4$. The flux lamps are mounted in a base-up configuration at the center of this sphere into a lamp socket supported from the top of the sphere. The lamp socket was a standard Edison screw type, with the four electrical leads (2 for lamp current and 2 for the lamp voltage measurement) attached directly to the socket. The circular baffle, also coated with BaSO4, is suspended on wire supports from the wall of the sphere and was situated approximately halfway between the lamp and the detector port.

6 Uncertainty budget submitted by each participant

6.1 CENAM

Table 4. The uncertainty budget of CENAM.

Uncertainty Component (Integrating Sphere)	Type (A or B)	Uncertainty Contribution (%)
Uncertainty of primary standards used	B	0,25
Transfer to secondary or working standards (if used)	A	0,23
Aging and long-term drift of the standard lamps used since last calibration	B	0,22
Repeatability of the standard lamps used	A	0,06
Self-absorption correction	A	0,01
Spectral mismatch correction	B	0,03
Lamp operating current uncertainty	B	0,21
Repeatability of the test lamp measured	A	0,06
Relative combined standard uncertainty (%)		0,46
Relative expanded uncertainty (*k*=2) (%)		0,92

6.2 INTI

Table 5. The uncertainty budget of INTI.

Uncertainty Component (Goniophotometer)	Type (A or B)	Uncertainty Contribution (%)
Illuminance responsivity calibration of the photometer head- further breakdowns if available	B	0,33
Long term stability of the photometer head since last calibration	B	0,10
Uncertainty of rotating radius of the photometer head	B	0,21
Error caused by the dead angle of the goniophotometer	B	Not included
Stray light of goniophotometer (back reflection, etc.)	B	Not included
Absorption by lamp socket and lamp holder	B	Not included
Spectral mismatch of the photometer head	B	Not included
Sampling errors associated with angle intervals of scan	B	Not included
Mechanical accuracy of angle positions for photometer head	B	Not included
Uncertainty of operating current of test lamp	B	0,06
Repeatability of luminous flux of test lamp	A	0,04
Relative combined standard uncertainty (%)		0,41
Relative expanded uncertainty (*k*=2) (%)		0,82

6.3 INMETRO

Table 6. The uncertainty budget of INMETRO.

Uncertainty Component (Integrating Sphere)	Type (A or B)	Uncertainty Contribution (%)
Realization of the lumen or uncertainty of primary standards used	B	0,5
Repeatability of the standard lamps used	A	0,11
Self-absorption correction	A	0,2
Lamp operating current uncertainty	B	0,003
Repeatability of the test lamp measured	A	0,8
Relative combined standard uncertainty (%)		0,97
Relative expanded uncertainty (*k*=2) (%)		2

6.4 NIST

Table 7. The uncertainty budget of NIST.

Uncertainty Component (Absolute Integrating Sphere)	Type (A or B)	Uncertainty Contribution (%)
Uncertainty of the determination of the external beam flux		
The NIST illuminance unit realization	B	0,20
Transfer to standard photometers	B	0,03
Long-term drift of the standard photometers (1 year)	B	0,08
Photometer reference plane (0,5 mm in 1 m)	B	0,05
Aperture area A	B	0,05
Average illuminance factor k_a	B	0,02
Stray light in illuminance measurement	B	0,03
Drift of the external source during calibration	B	0,02
Random noise of the signal in measurement of E_c	A	0,03
Uncertainty of the lamp luminous flux with respect to the external beam flux		
Determination of the correction factor scf_e	B	0,05
Long-term drift of the correction factor scf_e (1 year)	B	0,05
Uncalculated scf_i (flux standard lamps)	B	0,05
Incident angle dependence correction factor k_b	B	0,03
Spectral mismatch correction factor ccf_i/ccf_e	B	0,02
Detector nonlinearity	B	0,02
Effect of heat by test lamp (200 W lamp)	B	0,01
Random noise in the measurement of the external beam	A	0,02
Random noise in the measurement of test lamp	A	0,03
Reproducibility of test lamp (typical = 0,1)	A	0,05
	Relative combined standard uncertainty (%)	0,25
	Relative expanded uncertainty (*k*=2) (%)	0,50

6.5 NRC

Table 8. The uncertainty budget of NRC.

Uncertainty Component (Integrating Sphere)	Type (A or B)	Uncertainty Contribution (%)
Realization of the lumen or uncertainty of primary standards used	B	1,00
Aging of the standard lamps	B	0,10
Self-absorption correction	A	0,02
Spectral mismatch correction	B	0,05
Lamp operating current uncertainty	B	0,08
Repeatability of the test lamp measured	A	0,10
Sphere photometer calibration factor	A	0,20
	Relative combined standard uncertainty (%)	1,03
	Relative expanded uncertainty (*k*=2) (%)	2,07

7 Results reported by the Participant NMIs

The results submitted by the participant NMIs for both measurement rounds are presented below.

Table 9. The results of CENAM

	Luminous flux (lm)		Uncertainty
Lamp	Round 1	Round 2	*U* (*k*=2)
Polaron P270	2612,6	2617,0	0,92 %
Polaron P466	2358,1	2356,6	0,92 %
Polaron P484	2421,3	2411,6	0,92 %
Osram F002	1999,4	2010,5	0,92 %

Table 10. The results of INMETRO

	Luminous flux (lm)		Uncertainty
Lamp	Round 1	Round 2	*U* (*k*=2)
Osram 544	2236,9	2239,8	2 %
Osram 546	2288,2	2283,2	2 %
Osram 627	2648,1	2645,5	2 %

Table 11. The results of INTI

	Luminous flux (lm)		Uncertainty
Lamp	Round 1	Round 2	*U* (*k*=2)
Gec 437	2648	2635	0,8 %
Gec 447	2738	2736	0,8 %
Gec 448	2779	2765	0,8 %

Table 12. The results of NIST

	Luminous flux (lm)		Uncertainty
Lamp	Round 1	Round 2	*U* (*k*=2)
Polaron TF9-1	2193	2193	0,5 %
Polaron TF9-2	2202	2202	0,5 %
Polaron TF9-3	2180	2180	0,5 %
Polaron TF9-4	2232	2231	0,5 %

Table 13. The results of NRC

	Luminous flux (lm)		Uncertainty
Lamp	Round 1	Round 2	*U* (*k*=2)
Polaron P514	2299	2304	2,07 %
Polaron P517	2219	2222	2,07 %
Polaron P518	2069	2069	2,07 %
Polaron P525	2169	2172	2,07 %

Analyzing the results form Round 1 and Round 2 measurements, the difference of all the results for all the lamps are within the reported uncertainties, and therefore is considered that stability and reproducibility of all the lamps were appropriate. No result was excluded for the analysis.

8 Results obtained by the pilot lab of the measurements of all lamps.

Table 14 Results of the pilot laboratory measurements

NMI	Lamp	Luminous Flux (lm)	U (k=2)
CENAM	Polaron P270	2614,0	0,9%
	Polaron P466	2361,0	0,9%
	Polaron P484	2424,0	0,9%
	Osram F002	2003,0	0,9%
INMETRO	Osram 544	2221,9	0,9%
	Osram 546	2264,9	0,9%
	Osram 627	2626,2	0,9%
INTI	Gec 437	2640,5	0,9%
	Gec 447	2742,2	0,9%
	Gec 448	2778,1	0,9%
NIST	Polaron TF9-1	2193,8	0,9%
	Polaron TF9-2	2196,2	0,9%
	Polaron TF9-3	2177,2	0,9%
	Polaron TF9-4	2228,1	0,9%
NRC	Polaron P514	2273,0	0,9%
	Polaron P517	2191,6	0,9%
	Polaron P518	2039,8	0,9%
	Polaron P525	2143,3	0,9%

9 Data analysis

9.1 Laboratory ratios to pilot lab

The following notations are used.

$\Phi_{i,j}^{\mathrm{P}}$	Total luminous flux of lamp *j* of laboratory *i* measured by the pilot lab
$u_{\mathrm{rel}}(\Phi_{i,j}^{\mathrm{P}})$	Relative standard uncertainty of $\Phi_{i,j}^{\mathrm{P}}$
$u_{\mathrm{rel,T}}(\Phi_{i,j}^{\mathrm{P}})$	Reproducibility uncertainty of pilot lab measurement of lamp *j* of laboratory *i*
$\Phi_{i,j,r}$	Total luminous flux of lamp *j* of laboratory *i* measured by the laboratory *i* in round *r* with *r*=1 before transportation and *r*=2 after transportation
$u_{\mathrm{rel}}(\Phi_{i,j})$	Relative standard uncertainty of measurement by laboratory *i* for lamp *j*
n_{i}	Number of lamps used by laboratory *i*.

Following the scheme of the CCPR K3a and K4 comparisons, the lamps were calibrated at CENAM against its working standards. $\Phi_{i,j}^{\mathrm{P}}$ was measured by the pilot laboratory three times $1 \le k \le n(=3)$, as Eq. (1) below:

$$\Phi_{i,j}^{\mathrm{P}} = \frac{1}{n}\sum_{k=1}^{n} \Phi_{i,j,k}^{\mathrm{P}} \quad ; \tag{1}$$

and the standard deviations of the mean of these measurements, taken as the reproducibility uncertainties $u_{\mathrm{rel,T}}\left(\Phi_{i,j}^{\mathrm{P}}\right)$ of each lamp at the pilot laboratory, were calculated from Eq. (2):

$$u_{\mathrm{rel,T}}^{2}\left(\Phi_{i,j}^{\mathrm{P}}\right) = \frac{1}{n(n-1)}\sum_{k=1}^{n}\left(\frac{\Phi_{i,j,k}^{\mathrm{P}} - \Phi_{i,j}^{\mathrm{P}}}{\Phi_{i,j}^{\mathrm{P}}}\right)^{2}. \tag{2}$$

Following the same scheme of CCPR-K4 and the approved technical protocol, each NMI *i* reported two values $\Phi_{i,j,1}$ and $\Phi_{i,j,2}$, for each lamp *j* first and second rounds measurements. The detailed uncertainty budget of each participant is presented in section 6.

The ratio $R_{i,j}$ (laboratory *i* /CENAM) of each lamp *j* is calculated as the mean of these two values $\Phi_{i,j,1}$ and $\Phi_{i,j,2}$ divided by the CENAM value by:

$$R_{i,j} = \frac{\frac{1}{2}\sum_{r=1}^{2}\Phi_{i,j,r}}{\Phi_{i,j}^{\mathrm{P}}}; \tag{3}$$

The relative standard uncertainty of transfer of this ratio in the comparison is estimated from the reproducibility uncertainty at the pilot lab in Eq. (2) and from the two measurements by the participant:

$$u^2_{\mathrm{rel,T}}\left(R_{i,j}\right) = u^2_{\mathrm{rel,T}}\left(\Phi^{\mathrm{P}}_{i,j}\right) + \left(\frac{\Phi_{i,j,1} - \Phi_{i,j,2}}{\Phi_{i,j,1} + \Phi_{i,j,2}}\right)^2 \qquad (4)$$

In eq. (4), the first term represents the reproducibility of the pilot lab, the second term includes uncertainties from transfer standard lamp stability and the reproducibility of the participant (or the link lab). Note that the formula consistent with CCPR K4:1997-1998 is used here for the lamp stability factor.

The ratio for each participant *i* is given as the mean of $R_{i,j}$ for all lamps:

$$R_i = \frac{1}{n_i}\sum_{j=1}^{n_i} R_{i,j}; \qquad (5)$$

where n_i is the number of lamps at each laboratory *i*, and n_i =3 or 4 depending on the laboratory. Weighted mean (with transfer uncertainty) is not used here because one lamp that happened to have very small transfer uncertainty could dominate the transfer of the ratio. It was considered that all transfer lamps should be weighted equally (unless there was a very large change during transfer). The transfer uncertainty $u_{\mathrm{rel,T}}\left(R_i\right)$ of the mean of the ratio for all lamps in each laboratory *i* , *as well as considering the stability of the comparison scale at CENAM,* is given by:

$$u^2_{\mathrm{rel,T}}\left(R_i\right) = \frac{1}{n_i}\left[\frac{1}{n_i}\sum_{j=1}^{n_i} u_{\mathrm{rel,T}}\left(R_{i,j}\right)\right]^2 + u^2_{\mathrm{rel}}(\mathrm{CENAM\ system}). \qquad (6)$$

The term, $u_{\mathrm{rel}}(\mathrm{CENAM\ system})$, is the uncertainty associated with the long-term stability of the comparison scale at CENAM during the period of comparison, and was evaluated to be 0.21 %. The total uncertainty $u_{\mathrm{rel}}\left(R_i\right)$ is then given by

$$u^2_{\mathrm{rel}}\left(R_i\right) = u^2_{\mathrm{rel}}(\Phi_{i,j}) + u^2_{\mathrm{rel,T}}\left(R_i\right). \qquad (7)$$

The values of R_i and $u_{\mathrm{rel}}\left(R_i\right)$ for all laboratories are listed in Table 15.

Table 15. The results of the ratios to the pilot lab and their uncertainties.

Participant NMI	R_i	$u_{\mathrm{rel}}(\Phi_{i,j})$ *U*(k=2)	$u_{\mathrm{rel,T}}\left(R_i\right)$	$u_{\mathrm{rel}}\left(R_i\right)$
CENAM	0.9992	0.92 %	0.24 %	0.51 %
INMETRO	1.0081	2.00 %	0.22 %	1.02 %
INTI	0.9988	0.80 %	0.25 %	0.47 %
NIST (link lab)	1.0013	0.50 %	0.21 %	0.33 %
NRC (link lab)	1.0132	2.07 %	0.21 %	1.06 %

9.2 Link of SIM.PR-K4 to CCPR-K4

To obtain the link to the CCPR-K4 Key Comparison Reference Value, $R_{\mathrm{KCRV},i}$ is obtained from the ratios R_i of NIST and NRC in Table 15 and the individual results of NIST and NRC in CCPR K4:1997-1998 shown in Table 16. D_i is the link lab's relative difference from KCRV, $\Phi_{\mathrm{NMI}}/\Phi_{\mathrm{KCRV}}-1$, as reported in CCPR K4:1997-1998 report, and $u_{\mathrm{stability}}(D_i)$ is the estimated stability of the scale at each link laboratory over the time of CCPR K4:1997-1998 to this SIM K4 (2004 to 2005), including reproducibility of measurements. Both link laboratories maintained the set of standard lamps used in CCPR K4:1997-1998 and stability was checked.

Table 16. Calculations for linking to CCPR K4:1997-1998.

Link Lab	D_i	$u_{\mathrm{stability}}(D_i)$	$u_{\mathrm{rel,T}}(R_i)$	$R_{\mathrm{KCRV},i}$	$u_c(R_{\mathrm{KCRV},i})$	w_i	R_{KCRV}	$u(R_{\mathrm{KCRV}})$
NIST	-0,0021	0.12 %	0.21 %	1.0034	0.25 %	0.53	1.0034	0.18 %
NRC	0,0099	0.15 %	0.21 %	1.0032	0.26 %	0.47		

$R_{\mathrm{KCRV},i}$ (where *i*=4 for NIST or *i* =5 for NRC) is calculated by

$$R_{\mathrm{KCRV},i} = R_i/(D_i+1) \tag{8}$$

Weighting factor w_i was obtained by

$$w_i = 1/u_c^2(R_{\mathrm{KCRV},i})/\left[1/u_c^2(R_{\mathrm{KCRV,NIST}})+1/u_c^2(R_{\mathrm{KCRV,,NRC}})\right] \tag{9}$$

where

$$u_c^2\left(R_{\mathrm{KCRV},i}\right) = u_{\mathrm{stability}}^2(D_i)+u_{\mathrm{rel,T}}^2\left(R_i\right) \tag{10}$$

R_{KCRV} is given as a weighted mean of $R_{\mathrm{KCRV},i}$ from NIST and NRC:

$$R_{\mathrm{KCRV}} = R_{\mathrm{KCRV,NIST}}\cdot w_{\mathrm{NIST}} + R_{\mathrm{KCRV,NRC}}\cdot w_{\mathrm{NRC}} \tag{11}$$

The uncertainty of R_{KCRV} is given by

$$u^2(R_{\mathrm{KCRV}}) = \left[\frac{1}{u_c^2\left(R_{\mathrm{KCRV,NIST}}\right)}+\frac{1}{u_c^2\left(R_{\mathrm{KCRV,NRC}}\right)}\right]^{-1} \tag{12}$$

Thus, the results are listed in Table 3 and plot in Fig. 1 as an extension to the ones presented in CCPR-K4.

The unilateral degrees of equivalence D_i and U_i of each participant are calculated by

$$\begin{aligned} D_i &= R_i/R_{\mathrm{KCRV}}-1 \\ U_i &= 2\cdot\sqrt{u^2(R_{\mathrm{KCRV}})+u_{\mathrm{rel}}^2(R_i)} \end{aligned} \tag{13}$$

The final results of the unilateral degrees of equivalence are presented in Table 3 and Figure 1.

Table 3. Unilateral Degrees of Equivalence

NMI	D_i	U_i
CENAM	-0.41%	1.09%
INMETRO	0.48%	2.08%
INTI	-0.45%	1.01%

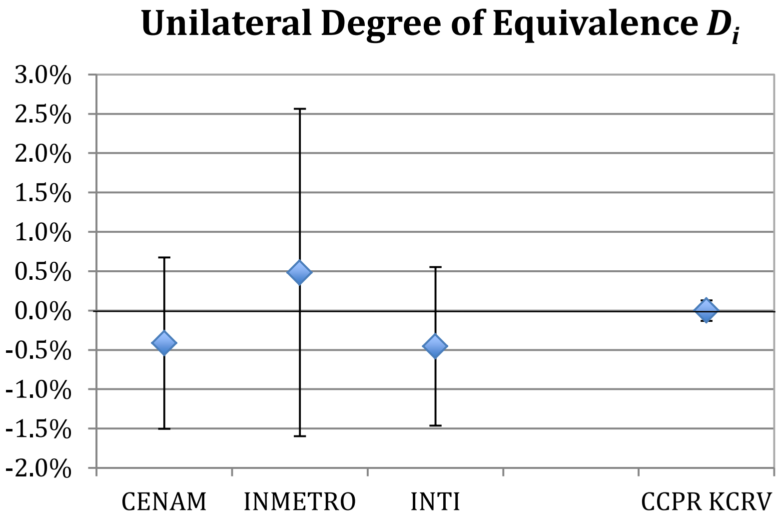

Figure 1. Link from SIM.PR-K4 to CCPR-K4:1997-1998.

Appendix A. Technical Protocol of SIM.PR-K4 Luminous Flux

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1. Introduction

The aim of the comparison is that of comparing the value of the magnitude of the lumen as maintained at each participating National Metrology Institutes (NMI). The results from the participating NMIs laboratories will be used to obtain a link to CCPR-K4 and derive the degree of equivalence of the participating NMIs.

This comparison will be participated by SIM NMIs with the *Centro Nacional de Metrología*, CENAM, (Mexican NMI) as pilot laboratory; and their standards will be compared in a "star-type" structure, using 3 or 4 lamps by each participant. The results of these comparisons will be the differences of the participating NMIs scales from the key comparison reference values for the luminous flux in CCPR K4.

The technical contact for this SIM.PR-K4 comparison is:

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2. Participants

Table 1 shows the list of the participating NMIs together with their acronym. Each participating NMI is asked to respond to the invitation, faxing back the "Response to Invitation" sheet (appendix A.1.) to CENAM.

Table 1 Participants of the SIM Key Comparison of luminous flux.

Acronym	Laboratory Name	Country
INTI	Instituto Nacional de Tecnología Industrial	Argentina
INMETRO	Instituto Nacional de Metrología, Normalização e Qualidade Industrial	Brazil
NRC	National Research Council	Canada
CENAM	Centro Nacional de Metrología	Mexico
NIST	National Institute for Standards and Technology	USA

The participating NMIs have declared the people listed in Table 2 as their respective technical contacts.

Table 2 NMIs technical contacts for this comparison.

NMI	Technical Contact(s)	
INTI	Dr. Jorge A. Cogno Tel. +54 11 4713 5311 Fax. +54 11 4713 5311 email: jac@inti.gov.ar	Eng. Karla Bastida Tel. +54 11 4713 5311 Fax. +54 11 4713 5311 email: bastida@inti.gov.ar
INMETRO	Dr. Iakyra B. Couceiro Tel. +55 21 2679 9026 Fax. +55 21 2679 9207 email: diopt@inmetro.gov.br	Mrs. Carla T. Coelho Tel. +55 21 2679 9026 Fax. +55 21 2679 9207 email: ctcoelho@inmetro.gov.br
NRC	Dr. Joanne Zwinkels Tel. +1 613 993 9363 Fax. +1 613 952 1394 email: Joanne.Zwinkels@nrc-cnrc.gc.ca	Dr. Arnold A. Gaertner Tel: +1 613 993 9344 Fax: +1 613 952 1394 email: arnold.gaertner@nrc-cnrc.gc.ca
CENAM	Dr. Eric Rosas Tel. +52 442 211 0500 Ext. 3341 Fax. +52 442 211 0553 email: erosas@cenam.mx	Eng. Irma Oidor Tel. +52 442 211 0500 Ext. 3319 Fax. +52 442 211 0553 email: ioidor@cenam.mx
NIST	Dr. Yoshi Ohno Tel. +1 301 975 2321 Fax. +1 301 840 8551 email: ohno@nist.gov	Mr. Yuqin Zong Tel. +1 301 975 2332 Fax. +1 301 840 8551 email: yuqin.zong@nist.gov

3. Transfer Standards

For this comparison the transfer standards will be either OSRAM Wi40/Globe, or Polaron LF 200 L lamps, on choice of the participating NMI; and three or four lamps will be used and prepared by each laboratory. Note that OSRAM Wi40/Globe lamps are no longer available for purchase.

Typical characteristics of the two types of lamps proposed are listed in Table 3. The lamps should be operated at the DC current that approximately reproduces the color temperature specified in Table 3. This DC current should be determined by each participant laboratory and for each lamp. The lamp voltage should also be measured and the type of lamp socket (four-pole or two-pole) should be reported.

The lamps should be operated in the base-up position and the participant laboratory must season and test them for stability before calibrating and sending to the pilot laboratory; also electrical polarity at which the lamps have been operated should be clearly indicated to the pilot laboratory.

Table 3 Typical characteristics of the transfer standard lamps.

Lamp	Osram Wi40/Globe	Polaron LF 200L
Luminous flux (nominal value)	2 500 lm	2 500 lm
Lamp current	5,8 A	2,2 A
Lamp voltage	30 V	90 V
Correlated color temperature (recommended)	2 800 K	2 750 K

For the transportation of the transfer standards hand-carrying is highly recommended in order to prevent damages to the lamps.

4. Type of Comparison

This comparison is planned to be a star-type due to the following advantages:

- Allowance of a direct comparison of the transfer standards,
- Reduction of the duration of the comparison,
- Concentration of the measurement activities of the pilot laboratory in a single campaign.

Each participating NMI will measure the four transfer standard lamps and send the lamps to CENAM together with the first measurement results.

At CENAM, each lamp will be operated at least two times in order to get two sets of measurement results. (If the lamp does not repeat in reasonable range, measurement will be further repeated.) The operating time of each transfer lamp will be recorded. Then the transfer standards will be sent back to the participants for their second measurements. When the measurement is complete at the participating laboratory, the second measurement results should be reported immediately to CENAM. During the comparison period, the stability of the CENAM setup will be monitored by using reference and working standard lamps. The reference lamps will allow us to determine the aging of the working lamps.

5. Time Schedule

The comparison measurements by the pilot laboratory are proposed to start in December 2004, and finish by July 2005, according to the proposed schedule detailed in Table 4. Since the comparison will be a star-type one, the participating NMIs will be able to measure their standards at any moment starting in November 2004 and then send the lamps and first round results to CENAM for them to be measured as shown in Table 4.

Table 4 Schedule deadline dates for the comparison.

Activity	Deadline
Receipt of the invitation and comparison protocol by the participating NMIs	10/04
Reply forms send to CENAM	11/04
Procurement of lamps and seasoning, by participating NMI*	01/05*
First calibration of transfer standards by participating NMIs*	02/05*
First calibration data arrive at CENAM*	02/05*
Transportation of transfer standards to CENAM*	03/05*
Measurements at CENAM	07/05
Transportation of transfer standards to participating NMIs	07/05
Second calibration of transfer standards by participating NMIs	11/05
Second calibration data arrive at CENAM	12/05
Draft A of the comparison report	04/06
Collection of comments from participating NMIs	05/06
Final report	07/06

***** NRC from Canada will be receiving their new lamps from the supplier at some time in March 2005; therefore in their case the schedule will be shifted accordingly so that NRC lamps could be transported to CENAM by July 2005.

6. Reporting Results

On completion of the first measurements, the participant must submit the results to the pilot laboratory using the “First Round Measurement Results Report Sheet” in appendix A.3, along with shipment or transportation of the lamps. The information about the participant’s measurement facility must also be submitted by using the “Description of the Measurement Facility and Primary Scale” form included in appendix A.2.

After completion of the second measurements by the participating laboratory, the results must be submitted to the pilot laboratory using the “Second Round Measurement Results Report Sheet” provided in appendix A.4. The participating laboratory must also submit their uncertainty budget for the calibration of the transfer standard lamps, using the “Uncertainty Budget” form shown as a guide in appendix A.5. The uncertainty of measurement shall be estimated according to the *ISO Guide to the Expression of Uncertainty in Measurement*. Primary components of uncertainty and the uncertainty contributions should be listed, with the total uncertainty of luminous flux given as a relative combined standard uncertainty.

The pilot Laboratory will send these sheets by e-mail as a Microsoft Word ^{TM} document; and participating laboratories are requested to complete the required information, and send them electronically to the pilot laboratory. **In addition, the signed report sheets must be sent in paper form by mail; and in the event of any difference between the electronic and paper forms information, the paper forms will be considered to be the definitive version**. Before Draft A is prepared, each participant will have an opportunity to check that the data received by the pilot laboratory are correct. After Draft A is produced no changes of data or corrections of results will be permitted, except for clerical errors.

A.1. Response to Invitation

Participation in

SIM Key Comparison of Luminous Flux, SIM.PR-K4

This form should be returned to Eric Rosas at CENAM by November 30th, 2004 via Fax: ++ 52 442 211 0553

Participant Laboratory: ____.

Please check appropriate box.

☐ Decline the invitation to participate in the above mentioned comparison.

☐ Accept the invitation to participate in the above mentioned comparison, and will agree to follow all the rules and conditions described in the Technical Protocol. We will be using the following lamps as transfer standard:

Please check appropriate box.

☐ 3 OSRAM Wi40/Globe lamps
☐ 4 OSRAM Wi40/Globe lamps
☐ 3 Polaron LF 200 L or similar
☐ 4 Polaron LF 200 L or similar

The technical contact from our Laboratory for this comparison will be:
Title: ________ First Name: _______________. Middle Initial: ____.
Last (Family) Name: _____________________.
Telephone: _______________________.
Fax: ____________________________.
E-mail: __________________________.

Additional comments: ____
____
____
_______________________________________.

Authorization Signature: ________________________.
Date: ___________________.
Position: ______________________.

A.2. Description of the Measurement Facility and Primary Scale

Laboratory: ____.

This form is only provided as a guide. If the space allocated for the answer of any question is insufficient, please add more lines in this form (on Word) or use separate sheet. Publications, if any, can be referred to for the details.

Method of realization of the luminous flux unit or traceability route of the primary standards used by the participating laboratory:

____
____
____
____

Description of the measuring facility and technique (please include a schematic diagram if appropriate):

____
____
____
____

The maintenance of the primary standards including the date of last realization (or calibration):

____
____
____
____

Description of calibration laboratory conditions, as temperature, humidity, etc.:

____
____
____
____

Signature: _______________.

Date: __________________.

A.3. First Round Measurement Results Report Sheet

Laboratory: ____.

Please fill in the appropriate table and blanks.

First Round Measurement Results

Lamp identification	Lamp Type*	Lamp Current (A)	Lamp Voltage (V)	Total Luminous Flux (lm)	Standard Deviation of total flux (%)	Number of Runs	Relative Expanded Uncertainty (*k*=2) (%)	Burning Time (h)
Type of lamp socket (4-pole or 2-pole):								
Laboratory temperature: °C								

* Polaron or OSRAM.

Date(s) of measurements: ________________________________

Signature: _______________.

Date: __________________.

A.4. Second Round Measurement Results Report Sheet

Laboratory: ____.

Please fill in the appropriate table and blanks.

Second Round Measurement Results

Lamp identification	Lamp Type*	Lamp Current (A)	Lamp Voltage (V)	Total Luminous Flux (lm)	Standard Deviation of total flux (%)	Number of Runs	Relative Expanded Uncertainty (*k*=2) (%)	Burning Time (h)
Type of lamp socket (4-pole or 2-pole):								
Laboratory temperature: °C								

* Polaron or OSRAM.

Date(s) of measurements: _______________________________

Signature: _______________.

Date: __________________.

A.5. Uncertainty Budget

This form is provided as a guide for typical uncertainty components to be considered and the minimum information to be reported. A more detailed table may be prepared and submitted by participants.

Laboratory: ____.

An example of uncertainty budget for goniophotometric method

Uncertainty Component (Goniophotometer)	Type (A or B)	Uncertainty Contribution (%)
Illuminance responsivity calibration of the photometer head-further breakdowns if available	B	
Long term stability of the photometer head since last calibration	B	
Uncertainty of rotating radius of the photometer head	B	
Error caused by the dead angle of the goniophotometer	B	
Stray light of goniophotometer (back reflection, etc.)	B	
Absorption by lamp socket and lamp holder	B	
Spectral mismatch of the photometer head	B	
Sampling errors associated with angle intervals of scan	B	
Mechanical accuracy of angle positions for photometer head	B	
Uncertainty of operating current of test lamp	B	
Repeatability of luminous flux of test lamp	A	
Relative combined standard uncertainty (%)		
Relative expanded uncertainty (*k*=2) (%)		

An example of uncertainty budget for sphere photometry method.

Uncertainty Component (Integrating Sphere)	Type (A or B)	Uncertainty Contribution (%)
Realization of the lumen or uncertainty of primary standards used	B	
Transfer to secondary or working standards (if used)	A	
Aging and long-term drift of the standard lamps used since last calibration	B	
Repeatability of the standard lamps used	A	
Difference in lamp intensity distribution and sphere non-uniformity	B	
Near-field absorption by lamp socket and holders	B	
Self-absorption correction	A	
Spectral mismatch correction	B	
Lamp operating current uncertainty	B	
Repeatability of the test lamp measured	A	
Effect of heat from lamp on sphere coating reflectance	B	
Relative combined standard uncertainty (%)		
Relative expanded uncertainty (*k*=2) (%)		

Signature: _______________.

Date: _________________