COOMET.PR-K3.a Comparison of Luminous Intensity

Final Report

(COOMET project 368/BY/06)

Boris Khlevnoy[2], Olga Tarasova[1], Dmitriy Scums[1], Tatyana Gorshkova[2], Eugene Ivashin[2], Marian Krempasky[3], Alexander Kupko[4], Natalya Vyrodova[5], Emma Woolliams[6]

[1]*Belarussian State Institute of Metrology (BelGIM), Belarus*

[2] *All-Russian Research Institute for Optical and Physical Measurement (VNIIOFI), Russia*

[3]*Slovak Institute of Metrology (SMU), Slovakia*

[4] *National Scientific Center "Institute of Metrology" (NSC IM), Ukraine*

[5]*Kazakhstan Institute of Metrology (KazInMetr), Kazakhstan*

[6]*National Physical Laboratory (NPL), UK*

Pilot: Belarussian State Institute of Metrology (BelGIM), Belarus

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ABSTRACT

This report gives the results of the COOMET.PR-K3 comparison of Luminous Intensity. Five laboratories took part in the comparison. COOMET.PR-K3 was piloted by Belarusian State Institute of Metrology (BelGIM). The linkage to KCRV was provided through the participation of the All-Russian Research Institute for Optical and Physical measurement (VNIIOFI) and Slovak Institute of Metrology (SMU). Other participants were National Scientific Center "Institute of Metrology" (NSC IM), Ukraine and Kazakhstan Institute of Metrology (KazInMetr).

BelGIM, NSC IM and KazInMetr were non-linked laboratories. A set of three incandescent lamps was used as traveling comparison artefact. Degrees of equivalence of all three non-linked laboratories were within their expanded uncertainties.

Content

1 INTRODUCTION

This report describes an international Key Comparison COOMET.PR-K3a of luminous intensity, conducted by the Euro-Asian Cooperation of National Metrological Institutions (COOMET) as the Regional Metrology Organization (RMO) in accordance with the COOMET project 368/BY/06.

The Mutual Recognition Arrangement (MRA) was signed in 1999 with the objectives of establishing the degree of equivalence of national measurement standards and providing for the mutual recognition of calibration and measurement certificates issued by National Metrology Institutes (NMIs). Under the MRA the equivalence of national measurement standards maintained by the NMIs is determined by a set of Key Comparisons which are chosen and organised by the Consultative Committees of the International Committee for Weights and Measures (CIPM), working closely with RMOs. The Consultative Committee for Photometry and Radiometry (CCPR) identified several Key Comparisons, including CCPR-K3.a for luminous intensity and CCPR-K3b for luminous responsivity, which were carried out between 1997 and 2001. The CCPR-K3a results were published in 1999 [1, 2] and the CCPR-K3b results – in 2004 [3, 4].

The COOMET.PR-K3a Key Comparison was carried out to establish the degrees of equivalence with respect to the Key Comparison Reference Value (KCRV) for the following participating laboratories: the Belarusian State Institute of Metrology (BelGIM, Belarus), the National Scientific Center “Institute of Metrology” (NSC IM, Ukraine) and the Kazakhstan Institute of Metrology (KazInMetr, Kazakhstan). COOMET.PR-K3a was piloted by BelGIM. The All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI, Russia) and the Slovak Institute of Metrology (SMU, Slovakia) acted as link laboratories. Both link institutes, VNIIOFI and SMU, took part in CCPR-K3a and CCPR-K3b.

COOMET.PR-K3a was a star form comparison and used as artefacts a group of three tungsten incandescent lamp, which luminous intensity was measured by all the participants.

COOMET.PR-K3a was registered in the BIPM key comparison database (KCDB) in 2009 and followed the Technical Protocol approved by the CCPR Working Group for Key Comparisons (CCPR-WGKC) and published in KCDB. Measurements within COOMET.PR-K3a were performed in the period from 2011 to 2013. Data analysis and the report preparation were done in accordance with the "CCPR-G2 Guidelines for CCPR Comparison Report Preparation" [5] and “CCPR-G6 Guidelines for RMO PR Key Comparisons” [6].

2 ORGANISATION

2.1 PARTICIPANTS

Table 1. List of participants

	Institute	Short name	Contact Person	Contact Details
Link-laboratory	Slovak Institute of Metrology Karloveská 63 SK-842 55 Bratislava Slovakia	SMU	Marian Krempasky	Tel: +421 7 602 94 278 Fax: +421 7 654 29 592 Email: krempasky@smu.gov.sk
Link-laboratory	All-Russian research institute for optical and physical measurement 46, Ozernaya, 119361, Moscow, Russia	VNIIOFI	Tatyjana Gorchkova	Tel: +7 495 437 55 33 Fax: +7 495 437 31 47 Email: gortb@vniiofi.ru
Pilot	Belarussian State Institute of Metrology 93, Starovilensky trakt Minsk, 220053 Belarus	BelGIM	Olga Tarasova	Tel: +375 17 23 4 98 20 Fax: +375 17 28 80 938 Email: optic@belgim.by
	National Scientific Center “Institute of Metrology” 42, Mironositskaya 61002, Kharkov	NSC IM	Alexander Kupko	Tel: +38 057 704 97 46 Fax: +38 057 700 34 47 Email: kupkoad@metrology.kharkov.ua
	Kazakhstan Institute of Metrology 11, Orynbor 010000, Astana Republic of Kazakhstan	KazInMetr	Natalya Vyrodova	Tel: +7 7172 79 32 90 Fax:+7 7172 24 32 97 Email: natalya_14@mail.ru

BelGIM acted as a pilot.

VNIIOFI and SMU were link laboratories. VNIIOFI and SMU participated in the CCPR-K3.a and CCPR-K3.b comparisons.

To ensure the blindness of COOMET.PR-K3.a, a neutral partner took part in the comparison. All the participants (including the pilot) sent their measurement reports to the neutral partner (not to the pilot). The neutral partner collected all measurements reports and then forwarded them to the pilot for analysis. Dr. Roland Goeber from BIPM played a role of a neutral partner.

2.2 FORM OF COMPARISON

The comparison was carried out by means of calibrating a group of three transfer standard lamps, prepared at the pilot laboratory.

The form of the comparison was a “STAR”. The lamps were initially calibrated by the pilot (BelGIM), then sent to the first participant, then returned to the pilot for repeat calibration, then sent to the second participant and so on. Therefore, the measurement sequence was the following:

Pilot – Participant 1 – Pilot – Participant 2 – Pilot – Participant 3 – Pilot – Participant 4 – Pilot.

The pilot measured the lamps after each participant measurements. Analysis of the pilot measurements showed (see section 5) that the lamps were stable during whole the comparison period within the pilot random uncertainty. Taking this into account for the DoE analysis the comparison can be treated as a set of bilateral Link *i* – Participant *j* comparisons.

3 TRANSFER STANDARD LAMPS

Transfer artefacts were tungsten filament gas-filled lamps of the SIS40-100 type specially developed for luminous intensity measurements (Fig.1). The lamps were produced at “LISMA” factory in Saransk city in Russia in 1990. Such lamps are not produced any longer. This type of lamps was used as luminous intensity standard lamps in former Soviet Union and still is used in some countries.

Fig.1. Transfer luminous intensity standard lamp of SIS40-100 type

The main parameters of the lamps are:

- Type of lamp …………………………...… SIS40-100
- Nominal luminous intensity ……………… 100 cd
- Nominal color temperature ……………….. 2856 K
- Nominal voltage, DC ……………………… 40 V
- Approximate current, DC ………………….. 2 A

The lamps were operated with DC power where the lamp current was stabilized and acted as the setting parameter. The positive polarity was connected to the thread of the lamp cap. The current of each lamp was defined in such a way that the color temperature of the lamps was approximately 2856 K. Table 2 shows identifications of the lamps and their defined set currents.

Table 2. Identifications and set current of lamps

Lamp identification	**Lamp current, A**
№ 134-90	1,8890
№ 140-90	1,8658
№ 141-90	1,8652

The lamps were aligned in such a way that the axis of measurement was perpendicular to the filament plane and pass through the geometrical centre of the filament. The distance was measured from the centre of the filament. The distance from the lamp to a photometer varied between 1.8 m and 2.0 m from participant to participant.

The lamps were warmed at the working current before starting measurement for approximately 15 minutes. The ambient temperature in different laboratories varied within 20 °C to 23 °C.

The lamps were transported between participant laboratories as hand luggage.

4 SEQUENCE OF MEASUREMENTS

The measurements were performed in the period from August 2011 to December 2012 in the following sequence:

BelGIM – VNIIOFI – BelGIM – NSC IM – BelGIM – SMU – BelGIM – KazInMetr – BelGIM.

5 STABILITY OF LAMPS

Stability of the lamps was estimated from the pilot repeat measurements of luminous intensity. The results of the measurements are presented in Table 3.

Table 3. Lamps luminous intensity stability measured by the pilot

Date of measurement	Lamp № 134-90		Lamp № 140-90,		Lamp № 141-90,	
	Luminous intensity, cd	Voltage, V	Luminous intensity, cd	Voltage, V	Luminous intensity, cd	Voltage, V
Aug. 2011	113.61	41.470	111.49	40.024	107.14	40.042
Oct. 2011	113.59	41.468	111.50	40.063	107.15	40.039
June 2012	113.57	41.463	111.51	40.033	107.14	40.039
Sep. 2012	113.60	41.468	111.48	40.031	107.15	40.040
Dec. 2012	113.60	41.468	111.50	40.032	107.15	40.040

From the Table 3 one can see that instability of the lamps was less than 0.04 %.

6 MEASUREMENT RESULTS

This section presents measured luminous intensity values and reported combined uncertainties. Detailed descriptions of measurement facilities, procedures and uncertainty budgets are presented in Annexes

Some of participants could not fix the exact value of the lamp set current, presented in Table 2 They measured lamp luminous intensity at a bit different current. Actual current was also measured and reported together with the luminous intensity data. Therefore, the reported luminous intensity values *I* were corrected as following:

$$I_{\mathrm{corrected}} = I_{\mathrm{reported}} + \partial I/\partial J \cdot (J_{\mathrm{set}} - J_{\mathrm{reported}}) \qquad (1)$$

where J_{reported} and J_{set} are reported current and set current, respectively. The rate $\partial I/\partial J$ was estimated as 300 cd/A. Because the correction value is small, the uncertainty associated with the rate is negligible. The measurement results of the participants, reported and corrected) are presented in Tables 4 – 8. VNIIOFI and SMU performed several independent measurements of each lamp, but only the average values were reported.

Table 4. BelGIM results

Lamp number	Reported Current, A	Luminous intensity (reported) cd	Set Current, A	Luminous intensity (corrected), cd	
					Average
№ 134-90	1.8889	113.62	**1.8890**	113.65	
	1.8889	113.59	**1.8890**	113.62	**113.635**
№ 140-90	1.8660	111.49	**1.8658**	111.43	
	1.8660	111.50	**1.8658**	111.44	**111.435**
№ 141-90	1.8650	107.11	**1.8652**	107.17	
	1.8650	107.19	**1.8652**	107.25	**107.21**

Table 5. NSC IM results

Lamp number	Reported Current, A	Luminous intensity (reported) cd	Set Current, A	Luminous intensity (corrected), cd	
					Average
№ 134-90	1.8890	113.30	**1.8890**	113.30	
	1.8886	113.10	**1.8890**	113.22	**113.26**
№ 140-90	1.8661	111.60	**1.8658**	111.51	
	1.8657	111.40	**1.8658**	111.43	**111.47**
№ 141-90	1.8652	107.40	**1.8652**	107.40	
	1.8647	107.00	**1.8652**	107.15	**107.275**

Table 6. KazInMetr results

Lamp number	Reported Current, A	Luminous intensity (reported) cd	Set Current, A	Luminous intensity (corrected), cd	
					Average
№ 134-90	1.8887	113.744	**1.8890**	113.83	
	1.8886	113.692	**1.8890**	113.82	**113.825**
№ 140-90	1.8657	111.787	**1.8658**	111.83	
	1.8658	111.789	**1.8658**	111.78	**111.805**
№ 141-90	1.8651	107.910	**1.8652**	107.93	
	1.8652	107.755	**1.8652**	107.76	**107.845**

Table 7. VNIIOFI results

Lamp number	Reported Current, A	Luminous intensity (reported) cd	Set Current, A	Luminous intensity (corrected), cd
№ 134-90	1.8890	113.71	**1.8890**	**113.71**
№ 140-90	1.8658	111.63	**1.8658**	**111.63**
№ 141-90	1.8652	107.77	**1.8652**	**107.77**

Table 8. SMU results

Lamp number	Reported Current, A	Luminous intensity (reported) cd	Set Current, A	Luminous intensity (corrected), cd
№ 134-90	1.8890	115.46	**1.8890**	**115.46**
№ 140-90	1.8658	113.16	**1.8658**	**113.16**
№ 141-90	1.8652	110.99	**1.8652**	**110.99**

Table 9 summarizes the all participants luminous intensity data after correction including the reported measurement uncertainties.

Table 9. All participants measurements results after correction for lamp current

	Lamp № 134-90		Lamp № 140-90		Lamp № 141-90	
	Luminous intensity, cd	Reported Standard Uncertainty, %	Luminous intensity, cd	Reported Standard Uncertainty, %	Luminous intensity, cd	Reported Standard Uncertainty, %
BelGIM	113.635	0.37	111.435	0.37	107.21	0.37
NSC IM	113.26	0.57	111.47	0.57	107.275	0.57
KazInMetr	113.825	0.37	111.805	0.37	107.845	0.37
VNIIOFI	113.71	0.34	111.63	0.34	107.77	0.34
SMU	115.46	0.35	113.16	0.36	110.99	0.35

7 PRE-DRAFT A. RELATIVE DATA REVIEW

At the Pre-Draft A stage the Relative Data $R_{j,i}$ were calculated for each participant *j* and for each lamp *i* as:

$$R_{j,i} = \frac{I_{j,i}/I_{BelGIM,i} - 1}{\frac{1}{3}\sum_i \left(I_{j,i}/I_{BelGIM,i} - 1\right)} \tag{2}$$

where

$I_{j,i}$ - average luminous intensity value of the lamp *i* of the participant *j* after correction as it appears in Table 9;

$I_{BelGIM,i}$ - average luminous intensity value of the lamp *i* of the pilot (BelGIM) after correction as it appears in Table 9.

The Relative Data for all participants, excepted the pilot, are presented in the Table 10. The Relative Data values do not show the absolute differences between the participants and the pilot but give the information about discrepancies between different lamps measurement results submitted by the same participant.

Table 10. Relative data of the participants

Participant	**Relative Data**			**Combined participant + pilot standard uncertainties**
	Lamp 134	**Lamp 140**	**Lamp 141**	
NSC IM	-0.25 %	0.11 %	0.14 %	0.70
KazInMetr	-0.20 %	-0.03 %	0.23 %	0.52
VNIIOFI	-0.19 %	-0.08 %	0.27 %	0.50
SMU	-0.62 %	-0.68 %	1.30 %	0.51

The Relative data of NSC IM, KazInMetr and VNIIOFI are consistent within the combined participant + pilot standard uncertainties, shown in the last column of the Table 10.

The Relative Data of SMU are not consistent: the data for the lamp 141 differs from the data for other two lamps by the value larger than the expanded (k=2) combined uncertainty. After discussion with pilot SMU requested removing its data for the lamp 141 from the further comparison analysis.

8 MEASUREMENT RESULTS AFTER PRE-DRAFT A

The measurement results, as they formed after removal of SMU data for the lamp 141 at the stage of the Pre-draft A procedure, are presented in Table 11. These are the final version of the measurements results to be use for the comparison analysis.

Table 11. Final summary of measurements results after correction for lamp current and Pre-Draft A

	Lamp № 134-90		Lamp № 140-90		Lamp № 141-90	
	Luminous intensity, cd	Reported Standard Uncertainty, %	Luminous intensity, cd	Reported Standard Uncertainty, %	Luminous intensity, cd	Reported Standard Uncertainty, %
BelGIM	113.635	0.37	111.435	0.37	107.21	0.37
NSC IM	113.26	0.57	111.47	0.57	107.275	0.57
KazInMetr	113.825	0.37	111.805	0.37	107.845	0.37
VNIIOFI	113.71	0.34	111.63	0.34	107.77	0.34
SMU	115.46	0.35	113.16	0.36	Removed	

9 COMPARISON ANALYSIS

The analysis of the comparison results was performed following the “Guidelines for RMO PR Key Comparisons” (CCPR-G6) [6].

The aim of the analysis was the evaluation of the Degree of Equivalence (DoE) for each non-link laboratory, i.e. the discrepancy of a non-link laboratory scale from KCRV, defined at the CCPR-K3a key comparison.

The non-link laboratories of COOMET.PR-K3.a were BelGIM (Belarus), NSC IM (Ukraine) and KazInMetr (Kazakhstan).

The DoE evaluation was based on the results of the Link laboratories (SMU, Slovakia and VNIIOFI, Russia), shown in this COOMET comparison and the CCPR key comparisons.

9.1 DoE of the Link Laboratories

There were two CCPR-K3 comparisons: CCPR-K3a on Luminous Intensity with tungsten lamps as artefacts and CCPR-K3b on Luminous Responsivity with photometers as artefacts. The link laboratories, VNIIOFI and SMU, participated in both CCPR comparisons. The RMO comparison COOMET.PR-K3a has to be linked to CCPR-K3a. However, at the time of the COOMET comparison analysis it was realized (by comparing the results of CCPR-K3a and -K3b) that both link laboratories, VNIIOFI and SMU, changed their photometric scales between CCPR-K3a and CCPR_K3b. This becomes obvious from Fig. 2, which compares DoEs of participants of both comparisons. Actually, since K3a compares luminous intensity in candelas [cd] and K3b compares responsivity, which is inversely proportional to candela [1/cd], DoE in K3a and DoE in K3b of a same participant should ideally have the same absolute values (within the uncertainty of the participant) but opposite sign. One can see that for instance the DoE of LNE in CCPR-K3a was 0.89 %, but in CCPR-K3b became -0.80 % (change of absolute value is negligible comparing with uncertainties, and the sign changed from positive to negative), or the DoE of NIM was -0.16 %, but became +0.13 %, and so on for the most of participants. But not for VNIIOFI and SMU. Their DoEs did not change sign: they were 0.33 % for VNIIOFI and -0.36 % for SMU in K3a and became 0.3 % and -0.24 % in K3b. This means that photometric scales of VNIIOFI and SMU were changed in the period between two CCPR comparisons by the values of -0.63 % and 0.60 %, respectively.

Lab i	D_i / 10^{-2}	U_i / 10^{-2}
LNE-INM/Cnam	0.89	0.60
NMISA	0.51	0.88
NMIA	-0.07	0.60
NMIJ	-0.09	0.56
INRIM	-0.43	0.90
IO-CSIC	-0.48	0.72
NIM	-0.16	0.48
NIST	0.12	0.48
NPL	0.04	0.30
NRC	0.19	1.06
METAS	-0.50	1.12
MKEH	0.05	0.94
PTB	-0.31	0.40
SMU	-0.36	1.40
VNIIOFI	0.33	0.92
INTI	-0.25	0.74
BIPM	0.30	1.00

Lab i	D_i / 10^{-2}	U_i / 10^{-2}
LNE-INM	-0.80	0.57
IFA	0.38	0.61
*NMIA	0.09	0.39
HUT	-0.35	0.61
MSL	-0.81	0.51
(KRISS)	2.10	0.64
*NIM	0.13	0.30
NIST	-0.15	0.42
*NPL	-0.03	0.39
NRC	0.00	1.01
METAS	1.02	0.51
OMH	-0.37	0.57
*PTB	0.35	0.37
SMU	-0.24	1.54
VNIIOFI	0.30	0.49
BIPM	-0.16	0.51

Fig.2. DoEs of CCPR-K3a (left) and DoEs of CCPR-K3b (right)

Therefore, the CCPR-K3a DoEs of VNIIOFI and SMU, as they are published at KCDB and presented in Fig.2 (left), were no more valid at the time when COOMET.PR-K3a was performed, and thus, could not be used for evaluating DoEs of the COOMET comparison participants. Correspondingly corrected values of the CCPR-K3a DoEs for VNIIOFI and SMU were subsequently generated from the values of the CCPR-K3b DoEs for VNIIOFI and SMU and the DoEs of the common CCPR-K3 participants (participants, who took part in both comparisons CCPR-K3a and -K3b). The procedure of restoring was the following:

We assume that, if transferred into the respective other quantity (i.e. luminous intensity), the KCRV evaluated in CCPR-K3b is not identical to KCRV evaluated in CCPR-K3a, as different participants took part in both comparisons. However, we believe that both KCRVs would produce identical results (within the uncertainty of the KCRV) if only the same NMIs participated in both comparisons. Therefore, we calculate the reference values (for use within this report only) RVK3a and RVK3b based on the results of only the common participants, excluding VNIIOFI and SMU. We know that the VNIIOFI and SMU DoEs in respect to KCRV-K3b, as published in the final report of CCPR-K3b (and shown in the left table in Fig.2) are

$$D_{\text{VNIIOFI, K3b}} = 0.30\% \;\; ; \;\; D_{\text{SMU, K3b}} = -\,0.24\%$$

Then we calculate the difference of VNIIOFI and SMU in respect to RVK3b as

$$D_{\text{VNIIOFI, RVK3b}} = D_{\text{VNIIOFI, K3b}} - \Delta\text{RVK3b} \; ; \; D_{\text{SMU, RVK3b}} = D_{\text{SMU, K3b}} - \Delta\text{RVK3b} \qquad (3)$$

where ΔRVK3b is the difference between RVK3b and the value of the KCRV of the CCPR-K3b comparison.

We assume that the reference values RVK3a and RVK3b will produce identical results, because they are based on the results of the same participants. Therefore, the difference of VNIIOFI and SMU in respect to RVK3a can be approximated by:

$$D_{\text{VNIIOFI, RVK3a}} = -\,D_{\text{VNIIOFI, RVK3b}} \; ; \; D_{\text{SMU, RVK3a}} = -\,D_{\text{SMU, RVK3b}} \qquad (4)$$

Finally, we calculate the correspondingly corrected value of the VNIIOFI and SMU DoEs in respect to KCRV-K3a as

$$D^{\text{new}}_{\text{VNIIOFI,K3a}} = D_{\text{VNIIOFI, RVK3a}} + \Delta\text{RVK3a} \; ; \; D^{\text{new}}_{\text{SMU,K3a}} = D_{\text{SMU, RVK3a}} + \Delta\text{RVK3a} \qquad (5)$$

where ΔRVK3a is the difference between RVK3a and the value of KCRV of the CCPR-K3a comparison.

There was a sufficiently high number of 11 participants, except VNIIOFI and SMU, who participated in both comparisons, CCPR-K3a and CCPR-K3b to calculate meaningful RVK3s. Note, that some NMIs changed names: LNE-INM/CNAM, NMISA, NMIJ, INRIM, IO-CSIC, METAS and MKEH earlier were named "BNM-INM", "CSIR-NML", "ETL", "IEN", "IFA", "OFMET" and "OMH", respectively. The common participants are:

- LNE-INM/Cnam (France)
- NMIA (Australia)
- IO-CSIC (Spain)
- NIM (China)
- NIST (USA)
- NPL (UK)
- NRC (Canada)
- OMH (Hungary)
- METAS (Switzerland)
- PTB (Garmany)
- BIPM

RVK3a and RVK3b were calculated as weighted mean with cut-off:

$$\text{RVK3a} = \sum_i D_{i,K3a} \cdot w_{i,K3a} \tag{6}$$

$$\text{RVK3b} = \sum_i D_{i,K3b} \cdot w_{i,K3b} \tag{7}$$

where $D_{i,K3a}$ and $D_{i,K3b}$ are DoE of the common participants as published in KCDB and shown in Fig.2, $w_{i,K3a}$ and $w_{i,K3b}$ are weights calculated as

$$w_{i,K3a} = u_{adj}^{-2}\left(x_{i,K3a}\right) \Big/ \sum_i u_{adj}^{-2}\left(x_{i,K3a}\right) \tag{8}$$

$$w_{i,K3b} = u_{adj}^{-2}\left(x_{i,K3b}\right) \Big/ \sum_i u_{adj}^{-2}\left(x_{i,K3b}\right) \tag{9}$$

where $u_{adj}\left(x_{i,K3a}\right)$ and $u_{adj}\left(x_{i,K3b}\right)$ are standard uncertainties of the common participants measurements in CCPR-K3a and CCPR-K3b, respectively, after the cut-off procedure.

Table 12 presents the DoEs, standard uncertainties of measurements before and after cut-off and weights of all common participants for both CCPR comparisons.

Table 12. DoEs, uncertainties and weights of common participants for CCPR-K3a and -K3b.

Participant	CCPR-K3a				CCPR-K3b			
	$D_{i,K3a}$ %	$u\left(x_{i,K3a}\right)$ %	$u_{adj}\left(x_{i,K3a}\right)$ %	$w_{i,K3a}$	$D_{i,K3b}$ %	$u\left(x_{i,K3b}\right)$ %	$u_{adj}\left(x_{i,K3b}\right)$ %	$w_{i,K3b}$
LNE-INM/Cnam	0.89	0.29	0.29	0.11	-0.8	0.28	0.28	0.08
NMIA	-0.07	0.29	0.29	0.11	0.09	0.18	0.25	0.10
IO-CSIC	-0.48	0.35	0.35	0.07	0.38	0.30	0.30	0.07
NIM	-0.16	0.22	0.25	0.14	0.13	0.12	0.25	0.10
NIST	0.12	0.22	0.25	0.14	-0.15	0.20	0.25	0.10
NPL	0.04	0.12	0.25	0.14	-0.03	0.18	0.25	0.10
NRC	0.19	0.52	0.52	0.03	0.00	0.50	0.50	0.03
OMH	0.05	0.46	0.46	0.04	-0.37	0.28	0.28	0.08
METAS	-0.50	0.55	0.55	0.03	1.02	0.25	0.25	0.10
PTB	-0.31	0.18	0.25	0.14	0.35	0.17	0.25	0.10
BIPM	0.30	0.49	0.49	0.04	-0.16	0.25	0.25	0.10

The uncertainties of RVK3a and RVK3b were calculated as

$$u(\text{RVK3a}) = \left(\sum_i \frac{u^2(x_{i,K3a})}{u_{adj}^4(x_{i,K3a})}\right)^{1/2} \Big/ \sum_i u_{adj}^{-2}\left(x_{i,K3a}\right) \tag{10}$$

$$u(\text{RVK3b}) = \left(\sum_i \frac{u^2(x_{i,K3b})}{u_{adj}^4(x_{i,K3b})}\right)^{1/2} \Big/ \sum_i u_{adj}^{-2}\left(x_{i,K3b}\right) \tag{11}$$

The final equations for the new, restored, DoEs of VNIIOFI and SMU in respect to KCRV-K3a are:

$$D^{\text{new}}_{\text{VNIIOFI,K3a}} = (\text{RVK3a} - \text{KCRV-K3a}) + (\text{RVK3b} - \text{KCRV-K3b}) - D_{\text{VNIIOFI, K3b}} \tag{12}$$

$$D^{\text{new}}_{\text{SMU,K3a}} = (\text{RVK3a} - \text{KCRV-K3a}) + (\text{RVK3b} - \text{KCRV-K3b}) - D_{\text{SMU, K3b}} \tag{13}$$

The equations for uncertainties of these new DoEs are:

$$u\left(D^{\text{new}}_{\text{VNIIOFI,K3a}}\right) = \left(u^2(\text{RVK3a}) + u^2(\text{KCRV-K3a}) + u^2(\text{RVK3b}) + u^2(\text{KCRV-K3b}) + u^2\left(D_{\text{VNIIOFI,K3b}}\right)\right)^{1/2} \tag{14}$$

$$u\left(D^{\text{new}}_{\text{SMU,K3a}}\right) = \left(u^2(\text{RVK3a}) + u^2(\text{KCRV-K3a}) + u^2(\text{RVK3b}) + u^2(\text{KCRV-K3b}) + u^2\left(D_{\text{SMU,K3b}}\right)\right)^{1/2} \tag{15}$$

Taking into account that KCRV-K3a = 0, KCRV-K3b = 0, u(KCRV-K3a) = 0.09 %, u(KCRV-K3b) = 0.09 % (as published at KCDB) and the Table 2, we got the following values:

RVK3a = 0.01 % ; u(RVK3a) = 0.08 %
RVK3b = 0.06 % ; u(RVK3b) = 0.07 %

$$D^{\text{new}}_{\text{VNIIOFI,K3a}} = -0.22\ \% \ ;\ u\left(D^{\text{new}}_{\text{VNIIOFI,K3a}}\right) = 0.29\ \% \tag{16}$$

$$D^{\text{new}}_{\text{SMU,K3a}} = 0.32\ \% \ ;\ u\left(D^{\text{new}}_{\text{SMU,K3a}}\right) = 0.79\ \% \tag{17}$$

The values in (16) and (17) are the new, restored, values of VNIIOFI and SMU DoEs in respect to KCRV-K3a, which are used below in this report for analysis of DoEs of the non-linked participants of the COOMET-K3a comparison.

9.2 Consistency of Link laboratories

Difference between SMU and VNIIOFI at CCPR-K3a are

$$D_{\text{SMU}} - D_{\text{VNIIOFI}} = D^{\text{new}}_{\text{SMU,K3a}} - D^{\text{new}}_{\text{VNIIOFI,K3a}} = 0.32\ \% - (-0.22\ \%) = 0.54\ \% \tag{18}$$

However, the difference between SMU and VNIIOFI at COOMET.PR-K3.a, calculated as an average for the lamps 134 and 140, are:

$$\Delta_{\text{SMU-VNIIOFI}} = \frac{1}{2}\cdot\left(\left(\frac{I_{\text{SMU,134}}}{I_{\text{VNIIOFI,134}}}-1\right)+\left(\frac{I_{\text{SMU,140}}}{I_{\text{VNIIOFI,140}}}-1\right)\right) = 1.45\% \tag{19}$$

In the ideal case the difference between the link laboratories would be the same in both comparisons. However, as one can see from the equations 18 and 19 the difference changed. This COOMET to CCPR comparison change Δ_{Link} equals to

$$\Delta_{\text{Link}} = \Delta_{\text{SMU-VNIIOFI}} - \left(D_{\text{SMU}} - D_{\text{VNIIOFI}}\right) = 1.45\% - 0.54\% = 0.91\% \tag{20}$$

The link (i.e. disagreement between the link laboratories) can be consider as consistent if Δ_{Link} is within its uncertainty. Because Δ_{Link} is determined by non-reproducibility and instability, the uncertainty $u(\Delta_{Link})$ includes components associated with random effects, stability of the scales and stability of the artefacts in both comparisons, i.e.

$$u^2(\Delta_{Link}) = u^2_{SMU,st} + u^2_{SMU,r,KC} + u^2_{SMU,r,RMO} + u^2_{VNIIOFI,st} + u^2_{VNIIOFI,r,KC} + u^2_{VNIIOFI,r,RMO} + s^2_{KC} + s^2_{RMO} \quad (21)$$

were $u_{SMU,st}$ and $u_{VNIIOFI,st}$ are uncertainties associated with stability of the SMU and VNIIOFI scales, respectively; $u_{SMU,r,KC}$ and $u_{VNIIOFI,r,KC}$ are random uncertainties during the CCPR key comparison; $u_{SMU,r,RMO}$ and $u_{VNIIOFI,r,RMO}$ are random uncertainties during the RMO (COOMET) comparison; s_{KC} and s_{RMO} are artefact stability uncertainties during the CCPR and RMO comparisons.

Because there was no evidence of the artefact instability, s_{KC} = s_{RMO} =0.

The RMO comparison was carried out a long time (about 10 years) after the CCPR comparison. Therefore, the stability uncertainties were replaced by the systematic uncertainties for both laboratories and then sum of systematic and KC random uncertainty squares were replaced by the squares of combined standard uncertainties stated by the laboratories for the KC. Thus:

$$u^2(\Delta_{Link}) = u^2_{SMU,KC} + u^2_{SMU,r,RMO} + u^2_{VNIIOFI,KC} + u^2_{VNIIOFI,r,RMO} \quad (22)$$

were $u_{SMU,KC}$ and $u_{VNIIOFI,KC}$ are the standard uncertainties associated with the SMU and VNIIOFI DoEs, i.e. $u_{SMU,KC} = u(D^{\mathrm{new}}_{\mathrm{SMU,K3a}}) = 0.79$ % and $u_{VNIIOFI,KC} = u(D^{\mathrm{new}}_{\mathrm{VNIIOFI,K3a}}) = 0.29$ %. According to the COOMET.PR-K3.a participant uncertainty budgets $u_{SMU,r,RMO}$ = 0.01 % and $u_{VNIIOFI,r,RMO}$ = 0.08%.

Thus $u(\Delta_{Link})$ = 0.845 % and the expanded uncertainty $U(\Delta_{Link}) = 2 \cdot u(\Delta_{Link})$ = 1.69 %.

Conclusion: the change of the link laboratories difference Δ_{Link} of 0.91 % is within its expanded uncertainty of 1.69 %. Therefore, the link laboratories results were consistent.

9.3 Evaluation of DoE of non-link participant

All participants of the COOMET comparison measured the same artefact set, which were stable during the comparison (see the section 5). Therefore the comparison was treated as a set of bilateral comparisons between non-link and link laboratories. The same analysis method, A2.1 of CCPR-G6 was applied for all non-link laboratories.

DoE D_i of a non-link participant *i* was calculated in accordance with the equation 21 of CCPR-G6:

$$D_i = W_{SMU} \cdot D_{i(SMU)} + W_{VNIIOFI} \cdot D_{i(VNIIOFI)} \tag{23}$$

were $D_{i(SMU)}$ and $D_{i(VNIIOFI)}$ are difference of participant *i* from KCRV via SMU and VNIIOFI, respectively (equation 20 of CCPR-G6):

$$D_{i(SMU)} = D_{\text{SMU,K3a}}^{\text{new}} + \tfrac{1}{2}\textstyle\sum_j \left(I_{i,j}/I_{SMU,j} - 1\right) \tag{24}$$

$$D_{i(VNIIOFI)} = D_{\text{VNIIOFI,K3a}}^{\text{new}} + \tfrac{1}{3}\textstyle\sum_j \left(I_{i,j}/I_{VNIIOFI,j} - 1\right) \tag{25}$$

where *j* is a number of lamp and the second summation is the average difference of the luminous intensity, measured by a participant from that measured by a link laboratory. All three lamps data were analyzed for VNIIOFI while for SMU only two lamps, 134 and 140, were treated.

The weights of SMU W_{SMU} and VNIIOFI $W_{VNIIOFI}$ were calculated in accordance with the equation 22 and 23 of CCPR-G6, taking into account that more than 10 year had passed between the CCPR and COOMET comparisons, and therefore the uncertainties associated with stability of the link laboratories scales was considered equal to their systematic uncertainties during the KC. It was also assumed that the KC artefacts and the RMO artefacts were stable (i.e. s_{KC} = 0 and s_{RMO} = 0):

$$W_{SMU} = \frac{W}{\sigma_{SMU}^2}\ ; \qquad W_{VNIIOFI} = \frac{W}{\sigma_{VNIIOFI}^2}, \tag{26}$$

$$\text{were} \quad W = \frac{\sigma_{SMU}^2 \cdot \sigma_{VNIIOFI}^2}{\sigma_{SMU}^2 + \sigma_{VNIIOFI}^2}, \tag{27}$$

$$\sigma_{SMU}^2 = u_{SMU,KC}^2 + u_{SMU,r,RMO}^2 \quad \text{and} \quad \sigma_{VNIIOFI}^2 = u_{VNIIOFI,KC}^2 + u_{VNIIOFI,r,RMO}^2 \tag{28}$$

From the COOMET.PR-K3a participant uncertainty budgets $u_{SMU,r,RMO}$ = 0.01 % and $u_{VNIIOFI,r,RMO}$ = 0.08 %. Similar to the previous section, we assume that $u_{SMU,KC} = u\left(D_{\text{SMU,K3a}}^{\text{new}}\right) = 0.79$ % and $u_{VNIIOFI,KC} = u\left(D_{\text{VNIIOFI,K3a}}^{\text{new}}\right) = 0.29$ %.

Thus $W_{SMU} = 0{,}13$ and $W_{VNIIOFI} = 0{,}87$.

9.4 Evaluation of DoE uncertainty

The uncertainty of the unilateral DoE of participant *i* is given as an expanded uncertainty

$$U(D_i) = 2 \cdot u(D_i) \tag{29}$$

where the standard uncertainty was calculated as (see the equation 6 of CCPR-G6):

$$u^2(D_i) = u_{i,RMO}^2 + u_{KCRV}^2 + W_{SMU}^2 \cdot (u_{SMU,KC}^2 + u_{SMU,r,RMO}^2) + W_{VNIIOFI}^2 \cdot (u_{VNIIOFI,KC}^2 + u_{VNIIOFI,r,RMO}^2) \tag{30}$$

10 DoE of COOMET.PR-K3.a PARTICIPANTS

10.1 DoE of BelGIM

Table 12 presents the luminous intensity values of BelGIM, SMU and VNIIOFI for each traveling lamps. Table 13 presents the relative differences between BelGIM and the link laboratories.

Table 12. Luminous intensity values of BelGIM and link laboratories

	Luminous Intensity, cd		
	Lamp 134	**Lamp 140**	**Lamp 141**
BelGIM	113.635	111.435	107.21
SMU	115.46	113.16	-
VNIIOFI	113.71	111.63	107.77

Table 13. Relative differences between BelGIM and link laboratories

	BelGIM-Link relative Difference, %			
	Lamp 134	**Lamp 140**	**Lamp 141**	**Average**
BelGIM-SMU	-1.58%	-1.52%	-	-1.55%
BelGIM-VNIIOFI	-0.07%	-0.17%	-0.52%	-0.25%

The BelGIM difference to KCRV via SMU and VNIIOFI are (equations 24 and 25)

$$D_{BelGIM\,(SMU)} = 0.32\ \% - 1.55\ \% = -1.23\ \%$$

$$D_{BelGIM\,(VNIIOFI)} = -0.22\ \% - 0.25\ \% = -0.47\ \%$$

DoE of BelGIM is

$$D_{BelGIM} = W_{SMU} \cdot D_{BelGIM\,(SMU)} + W_{VNIIOFI} \cdot D_{BelGIM\,(VNIIOFI)} = 0.13 \cdot (-1.23\%) + 0.87 \cdot (-0.47\%) = \mathbf{-0.57\%}$$

Standard uncertainty of BelGIM measurements is 0.37%. Therefore, the standard and expanded uncertainties of BelGIM DoE are (equations 17 and 16):

$$u(D_{BelGIM}) = \left(u_{i,RMO}^2 + u_{KCRV}^2 + W_{SMU}^2 \cdot (u_{SMU,KC}^2 + u_{SMU,r,RMO}^2) + W_{VNIIOFI}^2 \cdot \left(u_{VNIIOFI,KC}^2 + u_{VNIIOFI,r,RMO}^2\right)\right)^{1/2} =$$
$$= (0.37^2 + 0.09^2 + 0.13^2(0.79^2 + 0.01^2) + 0.87^2(0.29^2 + 0.08^2))^{1/2} = \mathbf{0.47\ \%}$$

$$U(D_{BelGIM}) = 2 \cdot u(D_{BelGIM}) = \mathbf{0.94\ \%}$$

10.2 DoE of NSC IM

Table 14 presents the luminous intensity values of NSC IM, SMU and VNIIOFI for each traveling lamps. Table 15 presents the relative differences between NSC IM and the link laboratories.

Table 14. Luminous intensity values of NSC IM and link laboratories

	Luminous Intensity, cd		
	Lamp 134	**Lamp 140**	**Lamp 141**
NSC IM	113.26	111.47	107.275
SMU	115.46	113.16	-
VNIIOFI	113.71	111.63	107.77

Table 15. Relative differences between NSC IM and link laboratories

	NSC IM – Link relative Difference, %			
	Lamp 134	**Lamp 140**	**Lamp 141**	**Average**
NSC IM – SMU	-1.91%	-1.49%	-	-1.70%
NSC IM – VNIIOFI	-0.40%	-0.14%	-0.46%	-0.33%

The NSC IM difference to KCRV via SMU and VNIIOFI are (equations 24 and 25)

$$D_{NSC-IM(SMU)} = 0.32\ \% - 1.70\ \% = -1.38\ \%$$

$$D_{NSC-IM(VNIIOFI)} = -0.22\ \% - 0.33\ \% = -0.55\ \%$$

DoE of NSC IM is

$$D_{NSC-IM} = W_{SMU} \cdot D_{MSC-IM(SMU)} + W_{VNIIOFI} \cdot D_{BNSC-IM(VNIIOFI)} =$$

$$= 0.13 \cdot (-1.38\%) + 0.87 \cdot (-0.55\%) = \mathbf{-0.66\%}$$

Standard uncertainty of NSC IM measurements is 0.57%. Therefore, the standard and expanded uncertainties of NSC IM DoE are (equations 17 and 16):

$$u(D_{NSC-IM}) = \left(u_{i,RMO}^2 + u_{KCRV}^2 + W_{SMU}^2 \cdot (u_{SMU,KC}^2 + u_{SMU,r,RMO}^2) + W_{VNIIOFI}^2 \cdot \left(u_{VNIIOFI,KC}^2 + u_{VNIIOFI,r,RMO}^2\right)\right)^{1/2} =$$

$$= (0.57^2 + 0.09^2 + 0.13^2(0.79^2 + 0.01^2) + 0.87^2(0.29^2 + 0.08^2))^{1/2} = \mathbf{0.64\ \%}$$

$$U(D_{NSC-IM}) = 2 \cdot u(D_{KazInMetr}) = \mathbf{1.28\ \%}$$

10.3 DoE of KazInMetr

Table 16 presents the luminous intensity values of KazInMetr, SMU and VNIIOFI for each traveling lamps. Table 17 presents the relative differences between KazInMetr and the link laboratories.

Table 16. Luminous intensity values of KazInMetr and link laboratories

	Luminous Intensity, cd		
	Lamp 134	**Lamp 140**	**Lamp 141**
KazInMetr	113.825	111.805	107.845
SMU	115.46	113.16	-
VNIIOFI	113.71	111.63	107.77

Table 17. Relative differences between KazInMetr and link laboratories

	KazInMetr – Link relative Difference, %			
	Lamp 134	**Lamp 140**	**Lamp 141**	**Average**
KazInMetr – SMU	-1.42%	-1.20%	-	-1.31%
KazInMetr – VNIIOFI	0.10%	0.16%	0.07%	0.11%

The KazInMetr difference to KCRV via SMU and VNIIOFI are (equations 24 and 25)

$$D_{KazInMetr\,(SMU)} = 0.32\ \% - 1.31\ \% = -0.99\ \%$$

$$D_{KazInMetr\,(VNIIOFI)} = -0.22\ \% + 0.11\ \% = -0.11\ \%$$

DoE of KazInMetr is

$$D_{KazInMetr} = W_{SMU} \cdot D_{KazInMetr\,(SMU)} + W_{VNIIOFI} \cdot D_{KazInMetr\,(VNIIOFI)} =$$

$$= 0.13\cdot(-0.99\ \%) + 0.87\cdot(-0.11\ \%) = \mathbf{-0.22\ \%}$$

Standard uncertainty of KazInMetr measurements is 0.37%. Therefore, the standard and expanded uncertainties of KazInMetr DoE are (equations 17 and 16):

$$u(D_{KazInMetr}) = \left(u_{i,RMO}^2 + u_{KCRV}^2 + W_{SMU}^2 \cdot (u_{SMU,KC}^2 + u_{SMU,r,RMO}^2) + W_{VNIIOFI}^2 \cdot \left(u_{VNIIOFI,KC}^2 + u_{VNIIOFI,r,RMO}^2\right)\right)^{1/2} =$$

$$= (0.37^2 + 0.09^2 + 0.13^2(0.79^2 + 0.01^2) + 0.87^2(0.29^2 + 0.08^2))^{1/2} = \mathbf{0.47\ \%}$$

$$U(D_{KazInMetr}) = 2 \cdot u(D_{KazInMetr}) = \mathbf{0.94\ \%}$$

11 DoE SUMMARY

Summary of DoE with expanded uncertainties of all non-link participants of the key COOMET comparison COOMET.PR-K3.a are presented in Table 18 and Figure 1.

Table 18. Summary of DoE of all non-link participants

NMI	DoE, %	*U* (DoE), % *k*=2
BelGIM (Belarus)	**- 0.57**	**0.94**
NSC IM (Ukraine)	**- 0.66**	**1.28**
KazInMetr (Kazakhstan)	**- 0.22**	**0.94**

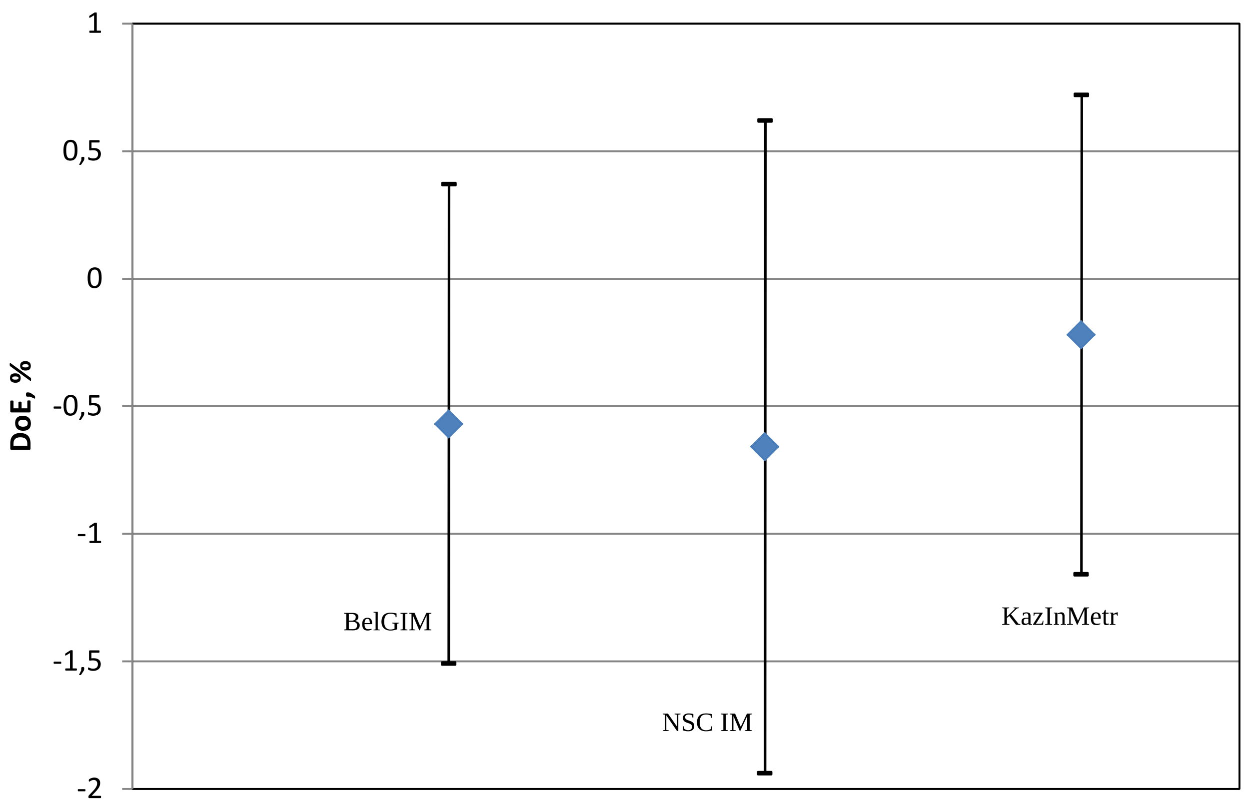

Figure 1. DoE and expanded uncertainties of COOMET.PR-K3a participants

12 ACKNOWLEDGEMENT

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Annex A: CCPR-K3a and CCPR-K3b Degrees of equivalence

The CCPR-K3a degrees of equivalence as published in KCDB [2].

Lab i	D_i / 10^{-2}	U_i / 10^{-2}
LNE-INM/Cnam	0.89	0.60
NMISA	0.51	0.88
NMIA	-0.07	0.60
NMIJ	-0.09	0.56
INRIM	-0.43	0.90
IO-CSIC	-0.48	0.72
NIM	-0.16	0.48
NIST	0.12	0.48
NPL	0.04	0.30
NRC	0.19	1.06
METAS	-0.50	1.12
MKEH	0.05	0.94
PTB	-0.31	0.40
SMU	-0.36	1.40
VNIIOFI	0.33	0.92
INTI	-0.25	0.74
BIPM	0.30	1.00

The CCPR-K3b degrees of equivalence as published in KCDB [4].

Lab i	D_i / 10^{-2}	U_i / 10^{-2}
LNE-INM	-0.80	0.57
IFA	0.38	0.61
*NMIA	0.09	0.39
HUT	-0.35	0.61
MSL	-0.81	0.51
(KRISS)	2.10	0.64
*NIM	0.13	0.30
NIST	-0.15	0.42
*NPL	-0.03	0.39
NRC	0.00	1.01
METAS	1.02	0.51
OMH	-0.37	0.57
*PTB	0.35	0.37
SMU	-0.24	1.54
VNIIOFI	0.30	0.49
BIPM	-0.16	0.51

Annex B: Measurement and uncertainty budget of link laboratory SMU

B.1 Make and type of the photometer :

For the comparison measurements was used photometer head LMT P15 F0T No1 S/N 0496301 made by Lichtmesstechnik (LMT). The photocurrent was measured with Iph I1000 (LMT).

B.2 Description of measuring technique:

Measurement configuration of listed devices from Table B1 is depicted on the Figure B1.

One measurement of luminous intensity of lamps consisted from 4 independent measurements including new alignment of standard lamp.

The determination of correlated color temperature was performed in 0°/45° geometry by spectrophotometer KONICA MINOLTA CS-1000A.

The results of this measurement are in Table B2. After determination of correlated color temperature of standards was started measurements of luminous intensity.

Table B1, Measurement devices

	Name of device	Producer
1.	Photometer head P15 F0T No1	Lichtmesstechnik, Germany
2.	Picoampermeter Iph I1000	Lichtmesstechnik, Germany
3.	Stabilized direct current source HP6477C	Hewlett Packard, USA
4.	Sshunt resistor RN/I with nominal value 0,01 Ω	Metra, Czech Republic
5.	Agilent 34401A Multimeter	Agilent, USA
6.	HP 3458A Multimeter	Hewlett Packard, USA
7.	Photometric bench FS – M – U 4.1	Russia
8.	IEE488 Cables	Hewlett Packard, USA
9.	TOSHIBA Notebook with GPIB USB interface and HP Vee software	TOSHIBA

Table B2. Laboratory transfer standard lamps

Type	Number	Correlated Color Temperature (K)
SIS 40-100	SIS 140	2849± 8 K
SIS 40-100	SIS 141	2849 ± 8 K
SIS 40-100	SIS 134	2847 ± 8 K

Each lamp was operated four times at the stated current and from these measurements the luminous intensity was determined for individual lamps.

Current was controlled as voltage drop on the shunt resistor and values of the voltage were taken from Multimeter 34401A. Simultaneously was controlled voltage at the cap of the lamp by second Multimeter HP3458A.

The photocurrent from photometer head LMT P15 F0T No1 was taken from Picoammeter Iph I1000. In the process of measurement was data acquiring by IEE488 cables from already named three devices to notebook with GPIB interface and by means of aquiring software HP Vee Pro (see Figure B1).

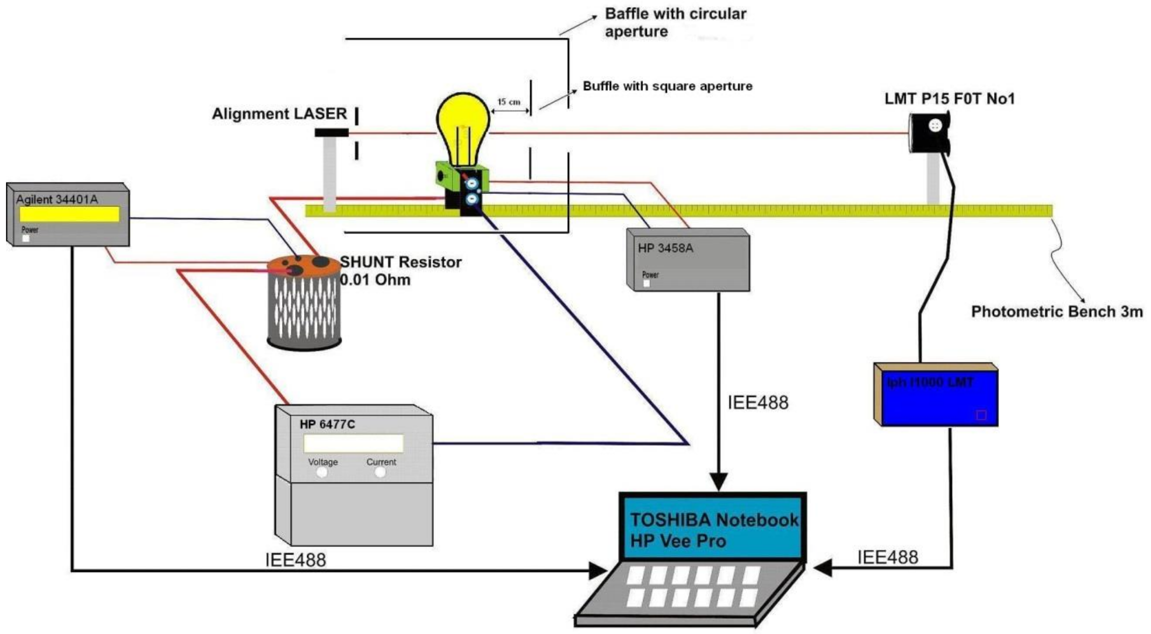


Figure B1. Measurement configuration

The photocurrent from photometer head LMT P15 F0T No1 was taken from Picoammeter Iph I1000. In the process of measurement was data acquiring by IEE488 cables from already named three devices to notebook with GPIB interface and by means of aquiring software HP Vee Pro (see Figure B1).

B.3 Establishment or traceability route of primary scale including date of last realisation and breakdown of uncertainty:

Realisation of luminous intensity at Slovak Institute of Metrology (SMU) is performed by detector based method with two temperature stabilized (maintained at 35 ± 0,1 °C) photometer heads made by Lichtmesstechnik (LMT) LMT P15 F0T No1 S/N 0496301 and LMT P15 F0T No2 S/N 0496302 as primary standard of luminous intensity with large area silicon photodiodes LMT P15 F0T matched to *V*(λ) function by sandwich type filter without diffusor.

The photometer heads are traceable to radiometric primary standards of optical power and irradiance TRAP quantum efficiency detectors QED200 with three cascade connected silicon diodes made by United Detector Technology USA.

For maintain and transfer of unit of luminous intensity at SMU are using primary set of secondary standards of luminous intensity (standard lamps type POLARON or OSRAM) at different distribution temperatures, which are traceable to photometer heads with known luminous responsivity (A/lx). Traceability route of luminous intensity unit at SMU is sketched in Figure 2. The recalibration of photometer head LMT P15 FOT No1 was performed on February 2012. The calculated luminous intesity at T=2856K for this photometer head is Sv = 51,709 +/- 0.169 nA/lx.

The uncertainty budget is shown in Table B3.

$$s_{\mathrm{v}} = \frac{\pi . d_{\mathrm{P15}}{}^{2}}{4} . \frac{y_{\mathrm{P15}}(555.2).R_{\mathrm{QED}}(555.2)}{c_{\Delta\lambda} . c_{T} . y_{\mathrm{QED}}(555.2).K_{\mathrm{M}}} .(1 + c_{\mathrm{LIN}} + c_{\mathrm{UV}} + c_{\mathrm{IR}} + c_{\mathrm{FATIGUE}}).10^{9}$$

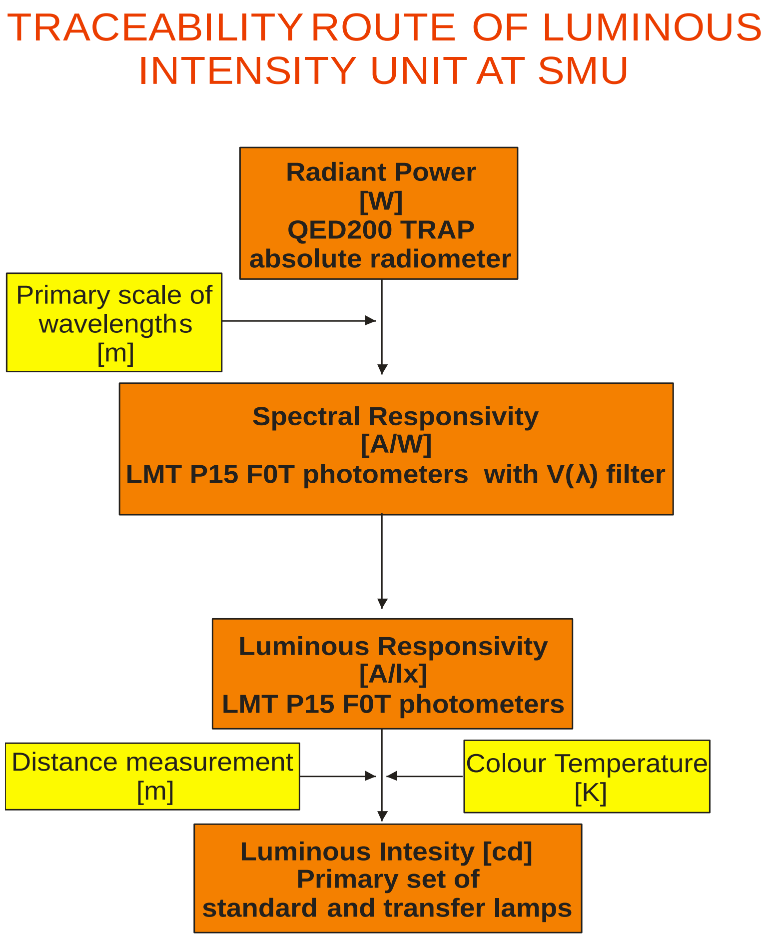


Figure B2. Traceability route of luminous intensity unit at SMU

Table B3. Uncertainty budget for s_V

Quantity	Value	Uncertainty	Sensitivity	Contribution
d_{P15}	0.015	2,00E-05	6.89455e3	0.13789
c_T	0.99391	9.32622e-5	-52.02596	-4.85205e-3
$c_{Dlambda}$	0.99883	6.78308e-4	-51.76988	-0.03512
$R_{QEDlamnorm}$	0.44709	4.4709e-4	115.6572	0.05171
Ratio(y_{P15}/y_{QED})	0.44377	4.92574e-4	116.5223	0.0574
c_{lin}	0	5.7735e-4	51.70913	0.02985
c_{UV}	0	3.33333e-4	51.70913	0.01724
c_{IR}	0	3.33333e-4	51.70913	0.01724
$c_{fatigueP15}$	0	5.7735e-4	51.70913	0.02985
I P15 No1 lam norm	2.194e-7	4.35807e-10	2.02265e6	8.81487e-4
I QED lam norm	4.944e-7	9.21574e-10	-8.97594e5	-8.27199e-4

B4 Description of calibration laboratory conditions: e.g. temperature, humidity etc.

Measurement conditions:
— Temperature **t_{lab} = (21,7 ± 0,3) °C**
— Relative humidity **e_{lab} = (56,7 ± 8) %**
—

B5 Operating conditions of the lamps: e.g. geometrical alignment, polarity, stray-light reduction etc.

Alignment: the holder with lamp was attached to the alignment device with 5 degrees of freedom plus it was possible with whole system (holder with lamp + alignment device) to move forward or backward.

Polarity: positive polarity at the cup thread

Stray light reduction: 2 baffles and a dark chamber over the photometric bench

B6 Results of measurements at SMU

Mathematical model for evaluation of luminous intensity each of the lamp is following:

$$I_{\mathrm{v}} = \left(\frac{J}{J_A}\right)^{-m_I}\left[\frac{1}{s_{\mathrm{v}}.(1+\alpha_T.\Delta T)}.y_{\mathrm{P15}}.(1-\frac{y_{\mathrm{dark}}}{y_{\mathrm{P15}}}-\frac{y_{\mathrm{stray}}}{y_{\mathrm{P15}}}).(d_2-d_1-d_{\mathrm{L}})^2\right].(1+\delta I_{vFatigue})+\delta I_{\mathrm{vJreg}}+\delta I_{\mathrm{vNoise}}$$

where m_{I} coefficient due to deviation of the lamp current to a nearby value J,

J_{A} is rated current at which it have to operate each of the lamp,

J is current measured across shunt resistor, α_T is temperature coefficient of LMT P15 No1 (K^{-1}),

ΔT is deviation of ambient temperature from rated temperature at which was photometer head calibrated,

y_{dark} is signal photometer when lamp is turned off,

y_{stray} is signal of photometer head when baffle is covered (stray signal),

y_{P15} is signal of photometer head when baffle is opened (direct signal from filament of the lamp),

d_2, d_1 and d_{L} are distances described above,

s_{v} is luminous responsivity of photometer head (nA/lx),

$\delta I_{\mathrm{vNoise}}$ contribution to luminous intensity uncertainty due to random noise which comes from lamp (lamp drift etc.),

$\delta I_{\mathrm{vJreg}}$ contribution to luminous intensity uncertainty due to regulation of current flowing across electrical circuit of the lamp and

$\delta I_{\mathrm{vFatigue}}$ is contribution to luminous intensity measurement due to burning time of the lamp.

The results with uncertainty budget for each lamps are showed in the following tables:

Table B4. Result of measurement with uncertainty budget of lamp 140

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ for (k = 1)	Sensitivity coefficient $c(x_i)$	Uncertainty contribution $u(I_v)$ for (k = 1)	Relative contribution $u_{rel}(I_v)$
s_v	51.709	0.169	-2.188	-0.37	-3.271e-3
y_{P15}	1.464e3	1.984	0.077	0.153	1.355e-3
d_2	2.232	3.524e-4	113.156	0.04	3.524e-4
d_1	0.229	3.109e-4	-113.156	-0.035	-3.109e-4
d_L	3,00E-03	3.524e-4	-113.156	-0.04	-3.524e-4
y_{dark}	1,00E-03	2.327e-4	-0.077	-1.798e-5	-1.589e-7
y_{stray}	-8.901e-4	5.427e-4	-0.077	-4.194e-5	-3.707e-7
α_T	1,00E-04	4.082e-5	-56.575	-2.31e-3	-2.041e-5
$\delta I_{vFatigue}$	0	1.433e-4	113.156	0.016	1.267e-6
δI_{vIreg}	0	1.501e-3	1	1.501e-3	1.327e-5
δI_{vNoise}	0	0.013	1	0.013	1.165e-4
J	1.8660	9.477e-5	-424.486	-0.04	-3.555e-4
ΔT	0.5	0.1	-0.011	-1.132e-3	-1,00E-05
m_I	7	0	0	0	0
J_A	1.8658	0	0	0	0
U_{lamp}	40.104	0	0	0	0
I_{vPA902}	113.16			0.41	(1 ± 0,00361)

Table B5. Result of measurement with uncertainty budget of lamp 141

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ for $(k = 1)$	Sensitivity coefficient $c(x_i)$	Uncertainty contribution $u(I_v)$ for $(k = 1)$	Relative contribution $u_{rel}(I_v)$
s_v	51.709	0.169	-2.146	-0.363	-3.271e-3
y_{P15}	1.436e3	1.671	0.077	0.129	1.164e-3
d_2	2.232	3.524e-4	110.988	0.039	3.524e-4
d_1	0.229	3.109e-4	-110.988	-0.035	-3.109e-4
d_L	3,00E-03	3.524e-4	-110.988	-0.039	-3.524e-4
y_{dark}	1,00E-03	2.327e-4	-0.077	-1.799e-5	-1.621e-7
y_{stray}	-7.286e-4	4.007e-4	-0.077	-3.098e-5	-2.791e-7
α_T	1,00E-04	4.082e-5	-55.491	-2.265e-3	-2.041e-5
$\delta I_{vFatigue}$	0	1.967e-4	110.988	0.022	1.772e-6
δI_{vIreg}	0	2.768e-3	1	2.768e-3	2.494e-5
δI_{vNoise}	0	0.014	1	0.014	1.262e-4
J	1.8654	4.693e-5	-416.499	-0.02	-1.761e-4
ΔT	0.5	0.1	-0.011	-1.11e-3	-1,00E-05
m_I	**7**	**0**	**0**	**0**	**0**
J_A	**1.8652**	**0**	**0**	**0**	**0**
U_{lamp}	**40.126**	**0**	**0**	**0**	**0**
$\boldsymbol{I_{vPA902}}$	**110.99**			**0.39**	**(1 ± 0,00353)**

Table B6. Result of measurement with uncertainty budget of lamp 134

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ for (k = 1)	Sensitivity coefficient $c(x_i)$	Uncertainty contribution $u(I_v)$ for (k = 1)	Relative contribution $u_{rel}(I_v)$
s_v	51.709	0.169	-2.233	-0.378	-3.271e-3
y_{P15}	1.494e3	1.696	0.077	0.131	1.135e-3
d_2	2.232	3.524e-4	115.459	0.041	3.524e-4
d_1	0.229	3.109e-4	-115.459	-0.036	-3.109e-4
d_L	3,00E-03	3.524e-4	-115.459	-0.041	-3.524e-4
y_{dark}	1,00E-03	2.327e-4	-0.077	-1.799e-5	-1.558e-7
y_{stray}	-7.953e-4	4.816e-4	-0.077	-3.723e-5	-3.224e-7
α_T	1,00E-04	4.082e-5	-57.727	-2.357e-3	-2.041e-5
$\delta I_{vFatigue}$	0	1.833e-4	115.459	0.021	1.588e-6
δI_{vIreg}	0	6.308e-4	1	6.308e-4	5.463e-6
δI_{vNoise}	0	0.014	1	0.014	1.244e-4
J	1.8892	2.526e-5	-427.812	-0.011	-9.358e-5
ΔT	0.5	0.1	-0.012	-1.155e-3	-1,00E-05
m_I	7	0	0	0	0
J_A	1.8890	0	0	0	0
U_{lamp}	41.546	0	0	0	0
I_{vPA902}	115.46			0.41	(1 ± 0,00352)

Resume of results of measurement at SMU (Slovak Institute of Metrology)

Table B7. Results of measurement of lamps measured at SMU

Lamp Number	I_v [cd]	$u(I_v)$ [cd]	$u_{rel}(I_v)$
SIS 140	113.16	± 0.41	. (1 ± 0,00361)
SIS 141	110.99	± 0.39	. (1 ± 0,00353)
SIS 134	115.46	± 0.41	. (1 ± 0,00352)

Operator: Stefan Nagy
Laboratory: Laboratory of photometry H120
Date: 1.10.2012

Annex C: Measurement and uncertainty budget of link laboratory VNIIOFI

C1. Realization of luminous intensity

The method of realization of the luminous intensity applied at VNIIOFI has remained unchanged since the CCPR-K3b comparison. The method is based on a blackbody with temperature of approximately 2856 K, equipped with a precise aperture [7]. The luminous intensity of the blackbody is defined according to the equation:

$$I_{BB} = A \cdot k_q 683 \cdot \int_{\lambda_1}^{\lambda_2} V(\lambda) \cdot \varepsilon \cdot L_\lambda(\lambda, T) d\lambda \tag{1}$$

where

$L_\lambda(\lambda,T)$ is spectral radiance calculated using the Planck law;

ε is the blackbody emissivity;

V(λ) is the spectral luminous efficiency for photopic vision;

A is the area of the blackbody aperture;

k_q is the correction for diffraction losses;

T is the blackbody temperature.

The main uncertainty components of the realization are associated with the blackbody temperature measurement, estimation of the blackbody emissivity, determination of the aperture area and the diffraction losses.

C2. Maintenance of the unit

The luminous intensity scale is transferred from the blackbody to and maintained with a group of photometers and photometric lamps. The photometer responsivity S_v is given by:

$$S_v = \frac{U_{BB} \cdot l_{BB}^2 \cdot K_{v,BB}}{I_{BB}} , \tag{2}$$

where

U_{BB} is the response of the photometer when it is illuminated by the blackbody;

l_{BB} is the dictance from the blackbody aperture to the photometer;

$K_{v,BB}$ is the spectral mismatch correction factor taking into account disagreement of the photometer relative spectral responsivity and V(λ), as well as the discrepancy of the blackbody temperature from 2856 K (Type A sourse);

I_{BB} is the luminous intensity of the blackbody calculated by the equation 1.

$K_{v,BB}$ is given by:

$$K_{v,BB} = \frac{\int_0^\infty E_\lambda(\lambda,T) V(\lambda) d\lambda \int_0^\infty E_\lambda(\lambda,T_A) S_v(\lambda) d\lambda}{\int_0^\infty E_\lambda(\lambda,T) S_v(\lambda) d\lambda \int_0^\infty E_\lambda(\lambda,T_A) V(\lambda) d\lambda} \tag{3}$$

$E_\lambda(\lambda,T)$ is the spectral irradiance of the blackbody;

$E_\lambda(\lambda,T_A)$ is the spectral irradiance of the Type A source (a Planckian radiator with the temperature T_A = 2856 K).

The same group of photometers was used for CCPR-K3.b and COOMET.PR-K3.a. The stability of the photometers had been checked time to time by means of comparing the photometers to each other and to the standard photometric lamps. The component associated with possible instability of the photometers between two comparisons was included to the uncertainty budget.

C3. Measurement of Luminous Intensity of the Comparison lamps

The Comparison lamps were measured by the standard photometers and the luminous intensity I_{CL} of each lamp was obtained as:

$$I_{CL} = \frac{U_{CL} \cdot l_{CL}^2}{S_v} \cdot K_v \qquad (4)$$

where

U_{CL} is the response of the photometer when it is illuminated by a comparison lamp;

l_{CL} is the distance fron the comparison lamp to the photometer;

K_v is the spectral mismatch correction factor taking into account the disagreement of the photometer relative spectral responsivity and V(λ), and the discrepancy of the lamp colour temperature from 2856 K (Type A sourse).

C4. Uncertainty budget

C4.1. Uncertainty budget of the luminous intensity realization and transfer to the standard photometer.

Uncertainty budget of the realization of luminous intensity is presented in Table C1.

Table C1

№	***Sources of uncertainty***	Relative standard uncertainty (k = 1), %	
		Type A	Type B
1	Blackbody temperature measurements		0.2
2	Blackbody emissivity		0.03
3	Blackbody uniformity		0.03
4	Blackbody aperture area		0.02
5	Diffraction losses		0.02
	Total standard uncertainty of realization	**0.21**	

Uncertainty budget of the photometer calibration is presented in Table C2.

Table C2

№	***Sources of uncertainty***	Relative standard uncertainty (k = 1), %	
		Type A	Type B
1	Realization of luminous intensity with the blackbody		0.21
2	Distance from blackbody to Photometer		0.03
3	Scattering light		0.05
4	Photometer signal measurement	0.01	
5	Spectral mismatch		0.02
6	Repeatability with independent alignment	0.05	
	Total standard uncertainty of photometer calibration	**0.22**	

4.1. Uncertainty budget of the comparison lamp measurement

Uncertainty budget of measurement of the comparison lamps (CL) is presented in Table C3.

Таблица C3

№	***Sources of uncertainty***	Relative standard uncertainty (k = 1), %	
		Type A	Type B
1	Photometer calibration		0.22
2	Long term stability of the scale (after CCPR-K3.b)		0.2
3	Distance from CL to photometer		0.1
4	Scattering light		0.03
5	Lamp current measurement		0.1
6	Photometer signal measurement	0.01	
7	Spectral mismatch		0.02
8	Repeatability with independent alignment of CL	0.08	
	Total standard uncertainty of CL measurement	**0.08**	**0.33**
		0.34	
	Expanded uncertainty (k = 2)	**0.68**	

Annex D: Measurement and uncertainty budget of KazInMetr

D1 Traceability of measurements

RSE “KazInMetr” receives the unit of luminous intensity from KRISS (Korea) through calibration of photometers. The “Inphora” photometer (serial No 090801) was used in the current comparisons as a standard photometer with the KRISS calibration certificate No 0900-PR-13, expanded uncertainty 0,54 % (k=2).

D2 Measurement conditions

The temperature during measurements was 21.6 °C.

The measurements of traveling lamps were conducted at the distance of 2 m from input aperture of the standard photometric head.

D3 Measurements of the luminous intensity of the traveling lamps

In order to measure the luminous intensity I_V, the traveling lamps and the photometric head of the standard photometer were aligned along the optic axis of the photometric bench at a distance of 2 m from each other. The traveling lamp illuminated the input aperture of the photometric head of the photometer.

D3.1 Functional scheme of measurement

The functional scheme for measuring the luminous intensity of lamps is shown in Fig. D1. Figure D2 presents the design of the measuring facility.

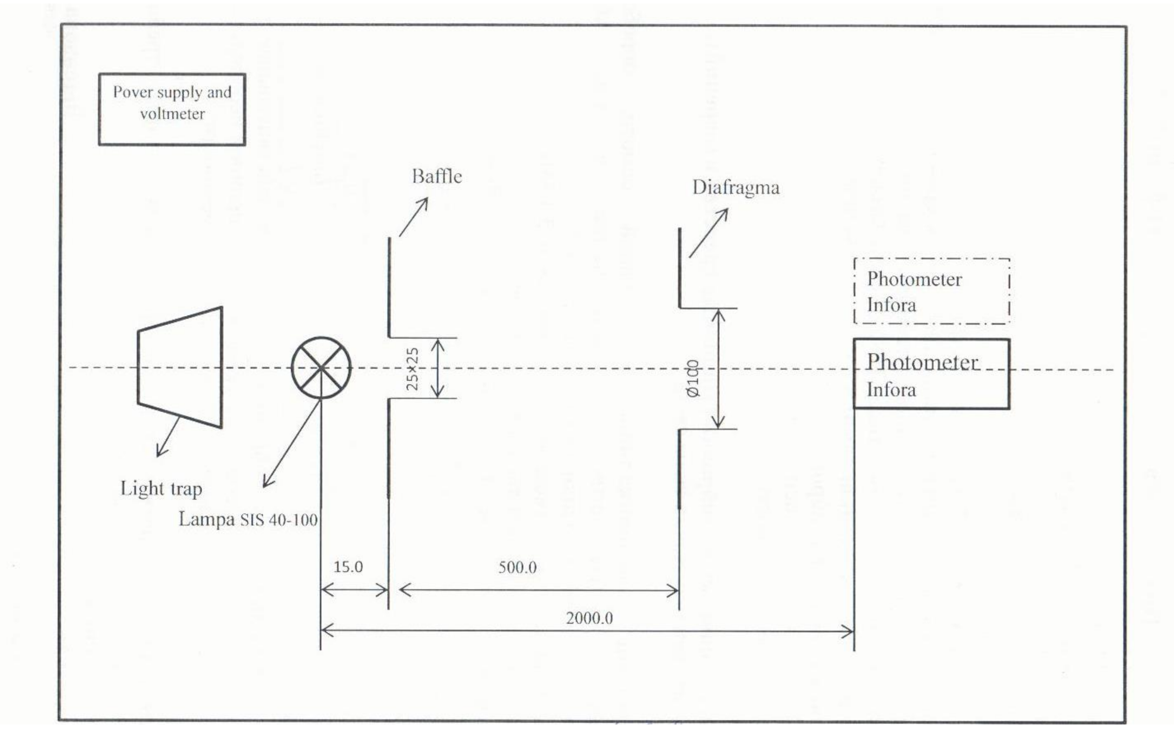


Figure D1 – Functional scheme for the measurement of luminous intensity

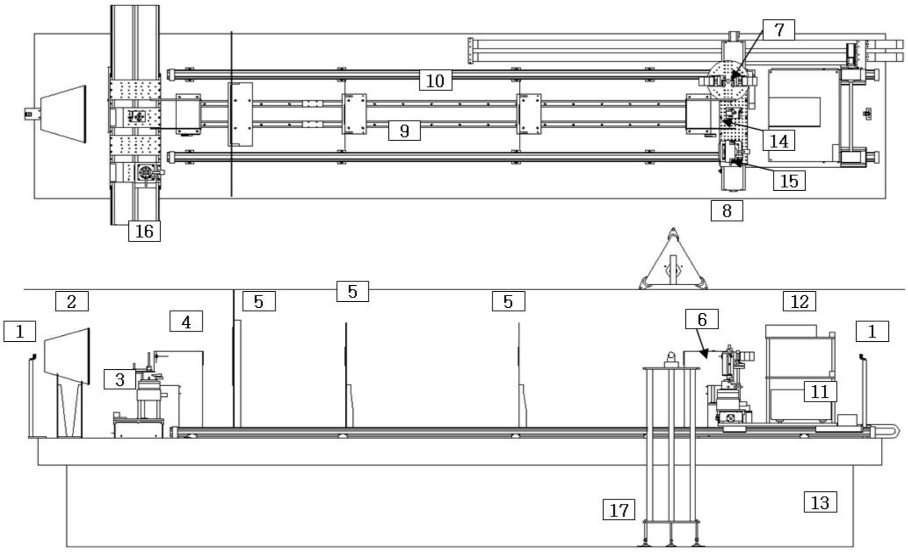


Figure D2 – Design of the measurement facility

1. Alignment lasers
2. Light trap
3. Lamp jig
4. Lamp alignment panel
5. Baffles
6. Detector alignment panel
7. Detector rotation stage
8. Detector linear stage
9. Accessory rail
10. Z Axis : Moving distance 4000mm
11. Spectro-radiometer
12. Picoameter
13. Optical Bench
14. Detector head of Spectro-radiometer
15. DUT jig
16. RX Axis : reference
17. Alignment telescope

D4 Measurement function of the traveling lamp luminous intensity I_V

$$I_V = S_V \cdot i \cdot l^2 \left(\frac{T_V}{T_A}\right)^m \cdot \left(\frac{V_j}{I_j R_j}\right)^{-m_I} \cdot X \qquad \text{(D1)}$$

Where $X = (1 - c_{stray} - c_a \Delta T)$

S_V - light sensitivity of the photometric head, lx/A;
i - the average photocurrent calculated as an average of 10 readings, A;
V_j – measured voltage of the resistor, V;
R_j – resistance of the resistor, Ohm;
I_j – nominal current of the lamp, A. No attributed uncertainty ;
l - distance between the center of the filament and the photometer head, m;
T_V - correlated color temperature, K;
T_A– correlated color temperature of the reference light source. No attributed uncertainty;
m – mismatch index of photometer;
m_I – exponent for the measurement of the lamp current, affecting the luminous intensity;
c_{stray} – relative correction for the effect of light irradiation diffusion;

$c_a \cdot \Delta T$- relative correction for the effect of ambient temperature fluctuations;
c(ε) – error due to independent adjustments of the traveling standard and the photometer.

D5 Uncertainty budget

The uncertainty budget of the measurement of the luminous intensity of the traveling lamps is presented in Table D1.

Table D1

Input quantity, x_i	Value, x_i	distribution	Standard uncertainty, $u(x_i)$	Sensitivity coefficient,c_i	contribution , $u_i(y)$, cd	Standard uncertainty of the luminous intensity, $u_{rel}(I_v)$, %
Light sensitivity, S_V	1,415E08 lx/A	B	3,82E05lx/A	8,03661E-07 cd/lx/A	0,306998	0,27
Photocurrent, i	0,200915 E-06A	A	2,185E-10 A	565999984,07 cd/A	0,123671	0,11
		B	0,275E-09 A		0,155649	0,14
Measured voltage of the resistor, V_j	0,0944044 V	A	0,0000181 V	-8358,144 cd/V	0,15128	0,13
		B	3,5E-07 V		0,0029 кд	0,003
Resistance of the resistor, R_j	0,049985 Ohm	B	0,00000145 Ohm	-15596,7815 cd/Ohm	0,022615	0,02
Distance, l	2 m	B	0,000144 m	113,718 cd/m	0,01637	0,014
Correlated color temperature,T_V	2850 K	B	13,3 K	0,0008 cd/K	0,011	0,01
Exponent for mis-match of photometer, m	0,02	B	0,0058	- 0,239 cd	-0,00139	-0,001
Exponent for the me-asurement of the lamp current, affect-ting the luminous intensity, m_I	6,87	B	0,1443	-0,14269 cd	-0,021	-0,02
Relative correction for the effect of light irradiation diffusion, c_{stray}	0,0005	B	0,000173	113,718 cd	0,0197	0,02
Relative correction for the effect of ambient temperature fluctuations, $c_a\Delta T$	-	B	0,0004	113,718 cd	0,05	0,04
Error due to indepen-dent adjustments of the traveling standard and the photometer, *c(ε)*	-	A	0,12 cd	-	0,12	0,11
Combined standard uncertainty, $u_c(I_V)$					0,418682	**0,37**

Annex E: Measurement and uncertainty budget of NSC IM

The National Scientific Center «Institute of Metrology» produces the independent realization of candela.

The functional diagram of candela realization and measuring lamp luminous intencity is shown in Figure E1.

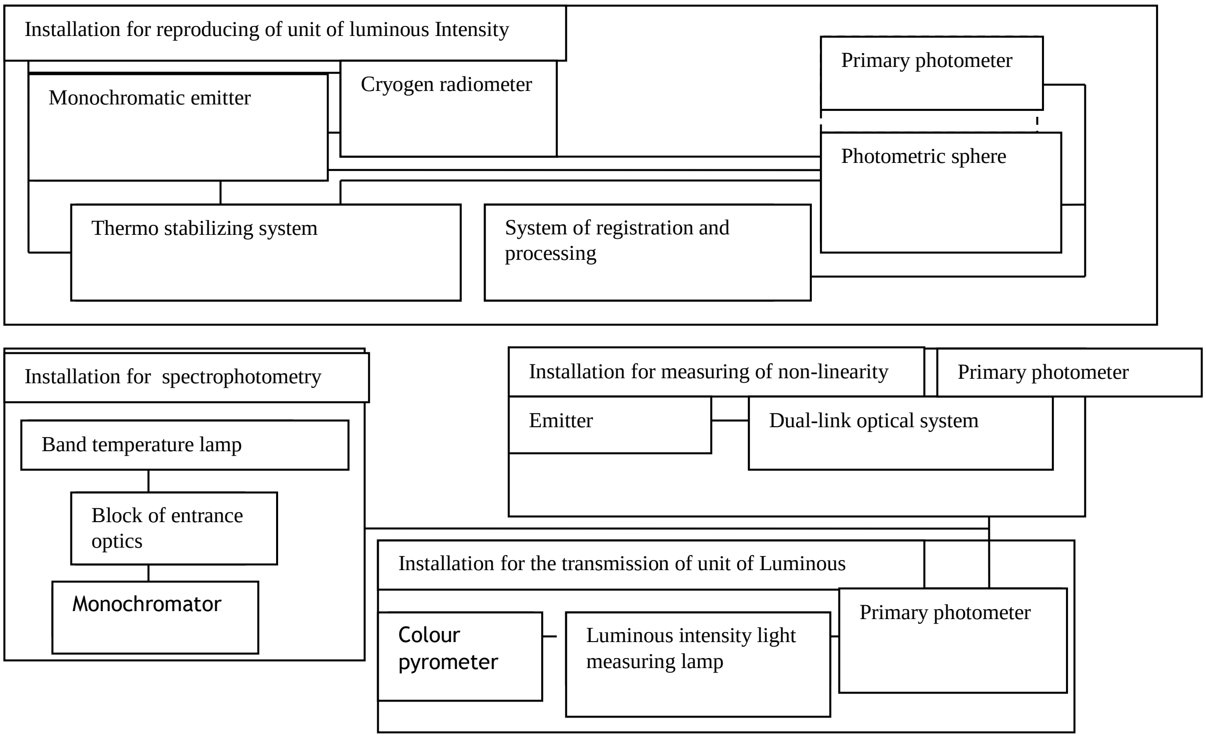


Figure E1. Functional diagram of candela realization and measuring lamp luminous intensity.

The appearance of the facility for reproducing candela, the unit of luminous intensity, is shown in Figure E2.

Figure E2. Appearance of installation for reproducing the unit of luminous intensity (candela)

Original appearance of spectrophotometry installation is shown in Figure E3, the installation for measuring non-linearity is shown in Figure E4, and the installation for transferring the unit of luminous intensity is shown in Figure E5.

Figure E3. Installation for spectrophotometry .

Figure E4. Installation for measuring non-linearity

Figure E5. Installation for transferring the unit of luminous intensity

Reproducing procedure was the following:

A mercury lamp equipped with a filter emits radiation of 546 nm. The radiation was focused into the receiving cone of the cryogenic radiometer. The radiation power was measured. Then the same beam was sent to the photometric sphere with a photodiode without a filter, and the responsivity of the sphere at the wavelength of 546 nm was determined. The photometric sphere was placed in a divergent beam of the same radiation, the illumination in the plane of the sphere input diaphragm was determined. Then a primary photometer (a temperature stabilized Si photodiode with a 4-component glass filter without a diaphragm and without a milk glass) was installed in the place of the photometric sphere, and responsivity of the photometer at the wavelength of 546 nm was determined.

Nonlinearity of the primary photometer was investigated using the installation for measuring the nonlinearity.

Then the relative spectral responsivity of the primary photometer was measured at the spectrophotometric facility by means of comparing with a trap detector and a nonselective film radiometer. Using the data of responsivity at the wavelength of 546 nm, the relative spectral responsivity was converted to absolute responsivity of the photometer to the Type A photometric source.

The main sources of uncertainty of the photometer responsivity are presented in Table E1.

Table E1. Uncertainty budget of the primary photometer responsivity

The source of uncertainty of the primary photometer	**Value, %**
Discrepancy of the relative spectral responsivity from V (λ): in the ranges 380-760 nm, 760 -1200 nm and bellow 380 nm, in total	0,040
Non-linearity of the photometer	0,32
Long-term stability and the ambient temperature sensitivity	0,24
Angular dependence and alignment	0,1
Combined standard uncertainty	0,43

Relative spectral distributions of the photometric lamp was measured at several power regimes by means of comparison with a strop lamp with known spectrum using the spectrophotometric facility (Fig. E3) Correlated color temperature of the photometric lamp was calculated for these regimes. Interpolating the obtained data, the lamp regime corresponding to the Type A source (Tcc = 2856 K) was determined.

Then the photometric lamp and the primary photometer were installed in the transfer facility (Fig. E5). Luminous intensity of the lamp was measured at several distances. The distance was measured with a telescope mounted on a r carriage with an attached vernier scale. The distance measurement values were corrected in such a way that the luminous intensity would be constant at difference distances. Finally the lamp luminous intensity was measured at the distance of 1.8 m.

The comparison traveling lamps were measured at the same transfer facility, which is a part of the National primary measurement standard facility for luminous intensity. Figure E6 schematically shows the structure of the facility.

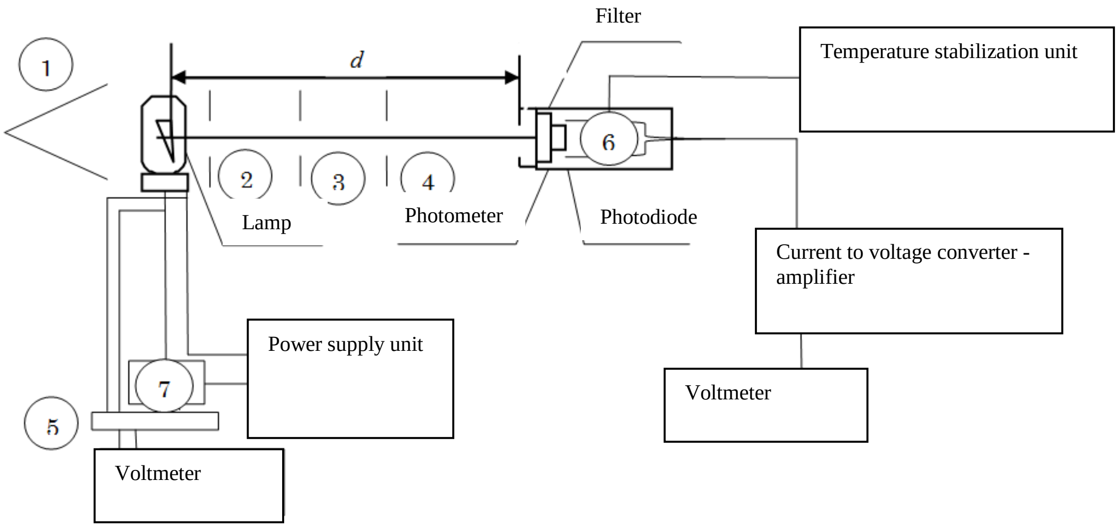


Figure 6. Scheme of installation for transferring the units of luminous intensity.

The entire installation is made in a light-insulated housing. Behind the lamp there is a radiation trap (1) made in the form of a cone with diameter of 0.3 m and depth of 0.8 m. In front of the comparison traveling lamp, type SIS 40-100, There is a shield (2) dimensions of which correspond to the USSR standard GOST 10771-82 “Filament lamps for light measurement. Specifications” (USSR State Committee for Standards M.-C .17). Between the lamp and the photometer there were too additional screens (3 and 4) with a hole diameter of 0.14 m. At the distance *d*=1.8 m from the lamp one of the three primary photometers was located. Photometers contain a correcting filter made of colored glass, a Si photodiode of FD-288 type and a temperature stabilization device (6).

The temperature stabilization device contacts the photodiode, and contains a temperature sensor and a heater. The stabilization temperature is approximately 40 °C. Time of temperature to become stable is about 50 minutes. The signal of the photodiode comes to the current-to-voltage converter, after which it is measured with a voltmeter. The lamp is supplied with a stabilized power supply. The current passes through the lamp and a standard resistance coil (7); the coil voltage drop is recorded by a voltmeter. The same voltmeter records the voltage of the lamp. The switch (5) provides alternate current measurement through the lamp and voltage on it.

The traveling lamp was exposed in such a way that its filaments would be placed vertically. Verticality was controlled by two plumb lines located in a plane perpendicular to the optical axis. The distance between the photometer and the lamp filament was measured with a telescope mounted on a carriage with an attached vernier scale.

The lamp was switched on gradually, step by step, within 30 minutes to avoid thermal shocks. After reaching the set current, the lamp was heated for another 20 minutes. At least 10 readings of the photometer were made. The lamp was switched off gradually within 20 minutes. The measuring procedure for each lamp was repeated with each of the three primary photometers.

General formula for measuring of luminous intensity was

$$I = d^2 y \left[\frac{K_{546} \int L(\lambda,T) V(\lambda) d(\lambda)}{s_0 \int L(\lambda,T) s_{rel}(\lambda) d(\lambda)} \right]$$

where

I is the traveling lamp luminous intensity

d is the distance from a lamp to the primary photometer

y is a signal of the primary photometer

K_{546} is the coefficient of relation between photometric and radiometric units

$L(\lambda, T)$ is the relative spectrum of the lamp

$V(\lambda)$ is the relative spectral light efficiency for photopic vision

s_o is the absolute responsivity of the primary photometer at the wavelength of 546 nm

s_{rel} is the relative spectral responsivity of the primary photometer

The uncertainty budget of the comparison traveling lamps measurement is shown in Table E1.

Table E1. Uncertainty budget of the SIS 40-100 lamps luminous intensity measurement performed at NSC "Institute of Metrology" (Ukraine)

Source of uncertainty	**Symbol**	**Value**		**Type**	**Distrib ution**	**Standard uncertainty of value**		**Relative Standard uncertainty of luminous intensity, %**
Photometer signal measurement (photometer and multimeter)	at	0.088	V	A	Gauss	0.0002	V	0.23
Photometer responsivity	s0	0.0028	(V/lx)	B	rect	0.000012	(V/lx)	0.43
Distance	d	1.8	m	A	gauss	0.001	m	0.06
		1.8	m	B	rect	0.0025	m	0.14
Lamp current	J	1.88	A	A	gauss	0.00009	A	0.03
								0.20
Shunt resistance		0.01	Om	B	rect	0.000002	Om	0.11
Lamp alignment		1		B	rect	0.001		0.08
Stray light		1	lx	B	rect	0.0001	lx	0.01
Photometer alignment		1		B	rect			0.08
Luminous intensity		103	kd					
Total Random uncertainty								**0.26**
Total Systematic uncertainty								**0.51**
Combined standard uncertainty								**0.57**

Annex F: Measurement and uncertainty budget of BelGIM

F1 Traceability of measurements

BelGIM national luminous intensity scale was traceable to the PTB (Germany) primary standard of luminous intensity through calibration of three photometric heads of P30SoT type (made by LMT, Germany), № 08B381; 08D3824 and 08B384.

F2 Measurement conditions

- ambient temperature 20,8 ° C;
- relative humidity 54,8%;
- the measurement distance is 1,696 m. Distance was measured from the filament to the aperture diaphragm of the photometric head.

F3 Measurement facility

Figure F1 shows a photo of the photometric heads P30S0T, mounted on the optical bench. The functional diagram of measuring luminous intensity is shown in Figure F2.

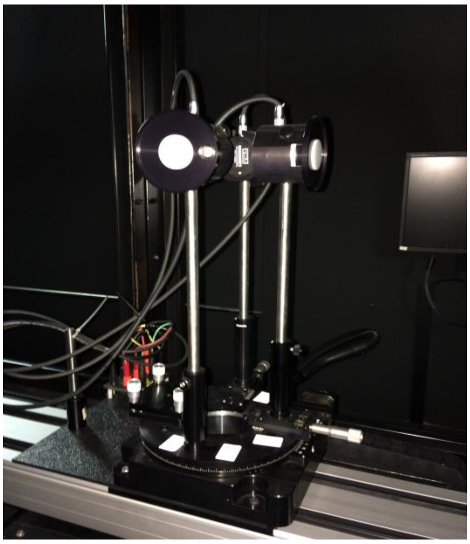
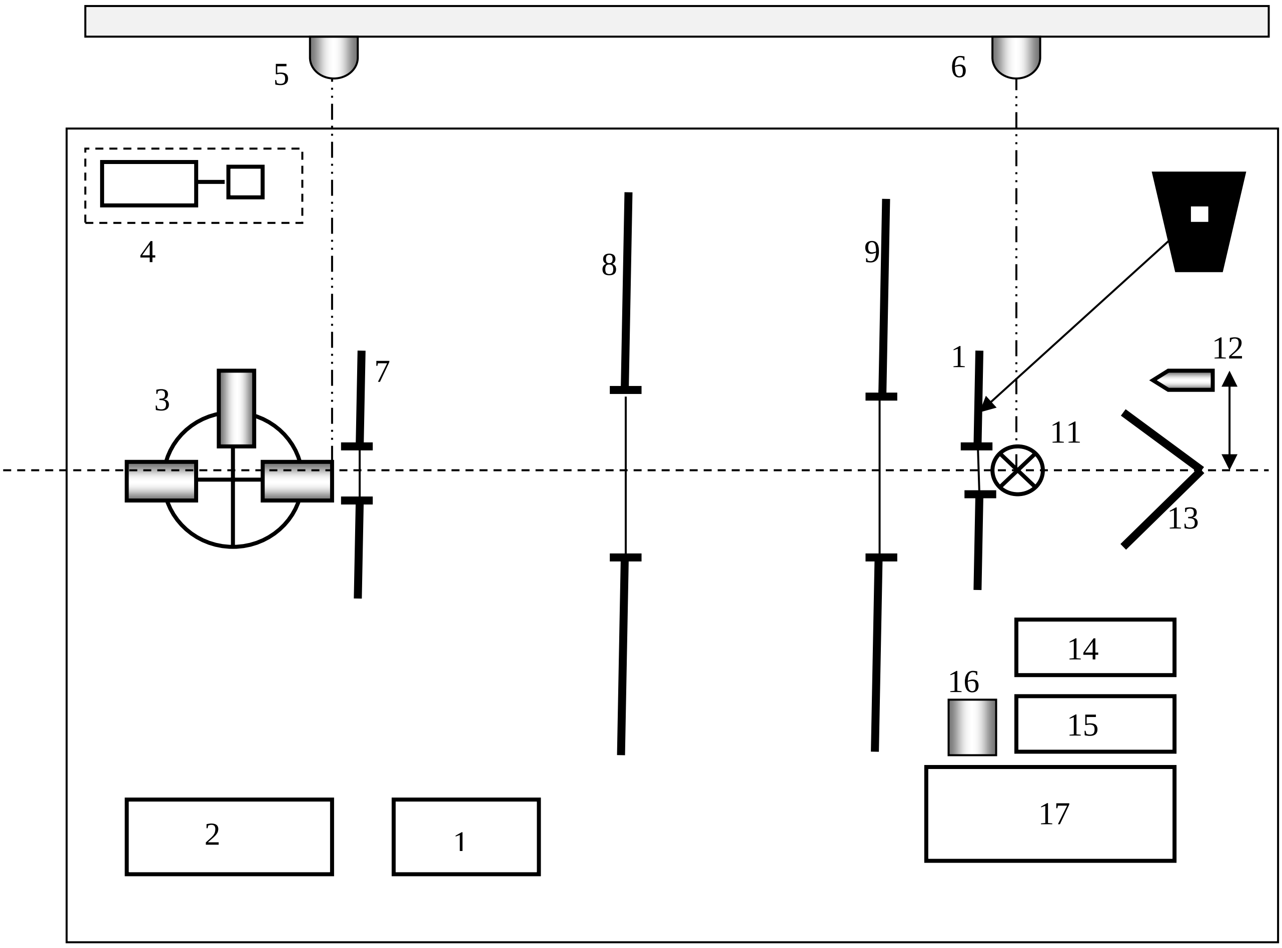


Figure F1. Photometric heads P30SoT in a holder on the optical bench



1 — PC; 2 — multimeter Agilent 3458A; 3 — 3 photometric heads P30SoT in the holder; 4 — colorimeter C 2100, 5, 6 —video cameras; 7, 8, 9, 10 — set of light-shielding diaphragms; 11 — standard lamp; 12— aligning laser;, 13 — stray light trap; 14 — multimeter Keythley 2100, 15 — multimeters Agilent 34410A; 16 — shunt resister P33; 17 — power supply Heinzinger PTNhp 125-20

Figure F2. Functional diagram of measuring luminous intensity

F4 Procedure of measurement of luminous intensity

Luminous intensity measurement was carried out using a group of photometers consisting of three P30SoT photometric heads and an Agilent 3458A multimeter. The photometric heads and a comparison lamp were mounted in special holders placed on a photometric bench.

Preliminary, the lamp and photometric heads were aligned using a video camera system (pos.5 and 6, Fig. F2).

The lamp was connected to the power supply of the Heinzinger PTNhp 125-20 type (pos 17, Fig. F2). Lamp currect and lamp voltage on the lamp socket were monitored during the measurements with multimeters Agilent 34410A anf Keythley 2100, respectively.

Luminous intensity I_{V} of the comparison traveling lamp was obtained using the relation

$$I_{\mathrm{V}} = \frac{i\,L^2}{S_{\mathrm{V}}}\left(\frac{T_{\mathrm{v}}}{T_{\mathrm{A}}}\right)^{m} \cdot \left(\frac{V_{\mathrm{j}}}{I_{\mathrm{j}}\,R_{\mathrm{j}}}\right)^{-m_1} \cdot X \quad , \tag{I1}$$

where i — photocurrent of the P30SoT photometric head measured by multimeter Agilent 3458A in amperes (A);

L — distance between the filament of the lamp and the aperture of the photometric heads P30SoT in meters (m). Distance L was calculated as

$$L = l_1 + l_2 \tag{I2}$$

where l_1 — the distance between the filament and the working side of the lamp's bulb, measured using a precision microscope ДИП-1; l_2 - the distance between the working side of the lamp's bulb and the aperture of the photometric head, measured with a distance meter Leica DISTO 540;

S_{V} — responsivity of P30SoT specified in the calibration certificate, A/lx

T_{V} — correlated color temperature of the lamp, determined during the measurement, K;

T_{A} - correlated color temperature of the CIE illuminant A, K;

V_{j} — average voltage at the lamp cap, V;

I_{j} — the lamp current, A;

R_{j} — the shunt resistance specified in the Calibration Certificate, Ohm.

m — mismatch index of photometer;

m_1– exponent for the measurement of the lamp current, affecting the luminous intensity;

$$X = \left(\left(1 - c_{\mathrm{stray}} - c_a \Delta t - w(\varepsilon)\right)\right) \tag{I3}$$

where c_{stray} — correction factor due to the influence of the stray light in the room where the measurements were made;

$c_a \Delta t$ — correction factor due to the influence of the ambient temperature in the room where the measurements were made;

$w(\varepsilon)$ — angular misalignment.

Measurements of the luminous intensity were carried out for each lamp using three photometric heads. The result of the measurement of the luminous intensity was taken as the averaged value.

F5 Uncertainty budget

The uncertainty budget of the measurement of the luminous intensity of the traveling lamps SIS 40-100 is presented in Table F1.

Table F1.

Sourse of uncertainty	Symbol	Relative standard uncertainty of luminous intensity, %	
		Random	Systematic
1	2	3	4
The signal from the photometric heads, estimated from the results of ten independent observations of the photocurrent, A	i	0.03	0.09
Conversion factor for photometric heads P30SoT, A/lx	S_{V}	-	0.30
The distance from the filament to the working side of the lamp's bulb, m	l_1	0.02	0.10
Distance between filament of the calibrated lamp and the aperture diaphragm of the photometric heads P30SoT, m	l_2		
correlated color temperature, K	T_{V}	-	0.02
The current in the lamp circuit, A	I_{j}	0.01	0.13
the voltage at the lamp cap, B	V_{j}	-0.01	-

Shunt resistance, Ом	R	-	0.02
Stray light, lx	c_{stray}	-	0.04
Mismatch index of photometer	m	-	0.02
Exponent for the measurement of the lamp current, affecting the luminous intensity	m_1	-	0.08
Ambient temperature, °C	$c_a \Delta t$	-	0.02
angular misalignment, °	$w(\varepsilon)$	0.04	-
Combined standard uncertainty, %		0.056	0.367
		0.37	
Expanded uncertainty (k=2), %		0.74	