

# **COOMET Key Comparison**

**Luminous Intensity COOMET.PR-K3a**  
**(COOMET project 368/BY/06)**

**Technical Protocol**

**(Draft 1)**

# 1 Introduction

This Technical Protocol (TP) describes an international key comparison of the values of luminous intensity, which are transferred by batches of incandescent lamps from the participants to the pilot laboratory.

This comparison is 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.

This key comparison is denoted COOMET.PR-K3a and registered at the key comparison database (KCDB) of the Bureau International des Poids et Mesures (BIPM) [<http://kcdb.bipm.org/>].

As a prototype of this Technical Protocol was used a draft of the Technical Protocol the EURAMET.PR-K3a comparison prepared by PTB who was also a pilot of the CCPR-K3a key comparison.

The Belarusian State Institute of Metrology (BelGIM) in Minsk (Belarus) acts as a pilot laboratory for this key comparison. All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI, Russia) and Slovak Institute of Metrology (SMU, Slovakia) act as link laboratories.

The key comparison is intended to determine the Degrees of Equivalence (DOE) for each participant and the associated expanded uncertainty. The DOE state the relative difference of participant's value with the Key Comparison Reference Value (KCRV), which were determined in the CCPR-K3a key comparisons, initialized by the Comité Consultative de Photométrie et Radiométrie (CCPR), The results of the CCPR-K3a were published in [1] in 1999. The DOEs of the CCPR-K3a participants are listed in the KCDB [2] and copied in Annex A.

Since the CCPR-K3a, the CCPR-KCRVs are maintained over nearly one decade by the participants of the CCPR comparisons and two of them are now link partners for the COOMET key comparisons. These partners transfer their maintained values by batches of lamps to the pilot laboratory, which measures the lamps and evaluates a weighted average as the COOMET-KCRVs.

Data analysis, report preparation and results publication will be done in accordance with the "Guidelines for CCPR Comparison Report Preparation".

The participants will provide the pilot with complete uncertainty budgets with all correlated contributions for a correct averaging of the measurement results. The stated uncertainties must be evaluated and reported according to the "Guide to the Expression of Uncertainty in Measurement" (GUM) [5].

The Technical Protocol is divided into two parts. The Part I is dealing with organizational and general information regarding the comparison. In the Part II, the principle models for an evaluation of the measurement results and uncertainties are summarized. The models are intended to harmonize the use of symbols and terms, and may also guide the participants how to describe their measurements. However they shall not restrict or direct a participant to modify or even change his calibration procedures. Examples, how to report

the data are given additionally. Finally, the determination of the DOE with associated uncertainty is explained.

## **2 Part I:**

### **2.1 Organization**

#### **2.1.1 Requirements to Participants**

All participants must be able to demonstrate independent traceability to the realization of the quantity, or make clear the route of traceability to the quantity via another named laboratory.

Present technical protocols and commit themselves to follow the procedures strictly.

Once the protocol and list of participants has been agreed, no change to the protocol or list of participants may be made without prior agreement of all participants.

#### **2.1.2 Participants' details**

<b>Institute</b>	<b>Shortcut</b>	<b>Contact Person</b>	<b>Contact Details</b>
Slovak Institute of Metrology Karloveská 63 SK-842 55 Bratislava Slovakia	SMU	Roman Dubnicka	Tel: +421 2 602 94 24 Fax: +421 2 654 29 595 Email: <a href="mailto:rdubnicka@smu.gov.sk">rdubnicka@smu.gov.sk</a>
All-Russian research institute for optical and physical measurement 46, Ozernaya, 119361, Moscow, Russia	VNIIOFI	Tatyjana Gorchkova	Tel: + 495 437 55 33 Fax: +495 437 31 47 Email: <a href="mailto:gortb@vniiofi.ru">gortb@vniiofi.ru</a>
Belarussian State Institute of Metrology 93, Starovilensky trakt Minsk, 220053 Belarus	BelGIM	Olga B. Tarasova	Tel: +375 17 23 4 98 20 Fax: +375 17 28 80 938 Email: <a href="mailto:khairova@belgim.by">khairova@belgim.by</a>
National Scientific Center "Institute of Metrology" 42, Mironositskaya 61002, Kharkov	NSC "IM"	Alexander D.Kupko	Tel: +38 057 704 97 46 Fax: +38 057 700 34 47 Email: <a href="mailto:kupkoad@metrology.kharkov.ua">kupkoad@metrology.kharkov.ua</a>
Kazakhstan Institute of Metrology 11, Orynbor 010000, Astana Republic of Kazakhstan	RSE "KazInMetr"	Berik T. Akirov	Tel: + 7172 79 32 68 Fax: + 7172 24 32 97 Email: <a href="mailto:kim_lab2@mail.ru">kim_lab2@mail.ru</a>

BelGIM will act as the pilot laboratory.

VNIIOFI and SMU will act as link laboratories.

To ensure the blindness of the comparison a Neutral Partner will take part. All the participants (including the pilot) must send their measurement reports to the Neutral

Partner (not to the pilot). The Neutral Partner collect all measurements reports and then direct them to the pilot laboratory for further analysis. Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D 38116 Braunschweig, Germany, Dr. Armin Sperling.

## 2.2 Form of comparison

The comparison will principally be carried out by the calibration of a group of transfer standard lamps. The used type of lamps have to show a reasonable stability and robustness.

Each participant will receive a set of seasoned lamps which will be preliminary selected at the pilot laboratory.

The minimum set of any transfer standards used for this comparison should be a group of three lamps. This minimizes the risk of unknown drift and damage and improves the ascertainment of the participants Degree Of Equivalence (DOE) (see Technical Protocol, Part II).

The artefacts (lamps) will initially be calibrated by the PILOT laboratory (BelGIM). Then they will be sent together with their individual nominal operating conditions (e.g. the operating current and geometrical information) to the PARTICIPANT 1 to perform calibration. Then they will be returned to the PILOT to carry out a repeated calibration to monitor drift. After that the lamp will be sent to the PARTICIPANT 2 for calibration, then return to the PILOT again, where the final measurements will be done.

Participant measurement reports are to be directed to the Neutral Partner as soon as possible and certainly within 6 weeks after the completion of all the measurements by the participant laboratory.

Within the time schedule, each laboratory has 8 weeks for calibration and transportation.

If for some reasons, the measurement facility is not ready or customs clearance takes too much time in a country, the participating laboratory must contact the pilot laboratory immediately to discuss further details and changes of the measurement timetable.

## 2.2.1 Timetable

month/year	Activity
5/2010	Receipt of the “Announcement” and “Reply form” by the participants
6/2010	“Reply form” sent to BelGIM
7/2010	Receipt of the “Technical Protocol” by the participants
8/2010	Comments sent to BelGIM
11/2010	1 st calibration of transfer standards (BelGIM) and transfer of result (ToR) to Neutral Partner
12/2010	Transportation of transfer standards to VNIIOFI
12/2010	Measurements at VNIIOFI and ToR to NP
1/2011	Transportation of transfer standards to BelGIM
2/2011	2 st calibration of transfer standards (BelGIM) and ToR to NP
3/2011	Transportation of transfer standards to SMU
5/2011	Measurements at SMU and ToR to NP
6/2011	Transportation of transfer standards to BelGIM
7/2011	3 st calibration of transfer standards (BelGIM) and ToR to NP
8/2011	Transportation of transfer standards to NSC “IM”
9/2011	Measurements at NSC “IM” and ToR to NP
10/2011	Transportation of transfer standards to BelGIM
11/2011	4 st calibration of transfer standards (BelGIM) and ToR to NP
12/2011	Transportation of transfer standards to RSE “KazInMetr”
01/2012	Measurements at RSE “KazInMetr” and ToR to NP
02/2012	Transportation of transfer standards to BelGIM
03/2012	5 st calibration of transfer standards (BelGIM) and ToR to NP
04/2012	Transfer of all individual results from Neutral Partner to BelGIM

end of 2012	draft A of report
2013	Final report



## **2.3 Handling of artefacts**

If ever possible, standard lamps should be transported by hand-carriage from the pilot laboratory to the participant and back again to the pilot. The standard lamps should only be handled by authorized persons and stored and packed in such a way as to prevent damage.

The standard lamps should be examined immediately upon receipt at final destination. However, care should be taken to ensure that the lamps and packaging have sufficient time to acclimatise to the actual environment thus preventing any condensation etc. The condition of the lamps and associated packaging should be noted and reported to the pilot laboratory. Please use the form in Annex D.

After the very first calibration at the pilot laboratory no cleaning of any lamp windows, apertures or envelopes should be attempted.

No parts other than noted within operating conditions belonging to specific lamps should be removed from or connected to this lamp.

If a standard lamp appears damaged a replacement if possible will be only available from the pilot laboratory.

During operation of the standard lamps any unusual occurrence, e.g. instability of voltage, instability in output etc. should be reported immediately to the pilot laboratory before proceeding.

Please inform the pilot laboratory via fax or e-mail when the measurement on the standard lamps are completed to arrange a suitable date for transportation or dispatch.

After the measurements, the lamps should be re-packaged in their original transit cases. Ensure that the content of the package is complete before shipment. Always use the original packaging.

## **2.4 Transport of artefacts**

It is of utmost importance that the artefacts be transported in a manner in which they will not be lost, damaged or handled by un-authorized persons.

Packaging for the artefacts should be suitably robust to protect the artefacts from being deformed or damaged during transit.

Artefacts should as a preference be carried by hand between participating laboratories

The pilot laboratory is responsible for the transport of the lamps and the costs involved.

Each participating laboratory covers the costs for its own measurements, as well as for any damages that may have occurred within its country.

The overall costs for the organization of the comparison are covered by the pilot laboratory.



## 2.5 Description of the standards

### 2.5.1 Transfer Standards used within the comparison

The measurement artefacts are specially developed transfer standard lamps for luminous intensity of the SIS 40-100 type.

The use of these lamps was decided and determined by the participants on request of the pilot laboratory.



SIS 40-100

**Fig. 1:** A type of the transfer standard lamp for luminous intensity

## 2.6 Measurement Conditions

### 2.6.1 Traceability

Length measurements should be independently traceable to the latest realisation of the meter.

Temperature measurements should be made using the International Temperature Scale of 1990 (ITS-90).

Electrical measurements should be independently traceable to the latest realisations of the amp and volt.

## 2.6.2 Measurands

The measurand is the luminous intensity of a lamp.

This photometric quantity should be measured for the defined operating conditions of each lamp, where the operating current acts as the setting parameter.

The measurements should be performed in suitable laboratory accommodation maintained at a temperature of 20 to 25 °C. The temperature of the laboratory during the time of the measurements should be reported.

The luminous intensity of the appropriate lamp should be measured independently at least 2 times.

Each independent measurement should consist of the lamp being realigned in the measurement facility and being switched off and on after a break of at least 1 h for each lamp. Each independent measurement set should be reported. It should be noted that each independent measurement may consist of more than one set of measurements, the exact number should be that normally used by the participating laboratory to obtain the appropriate accuracy as limited by the noise characteristics of their specific measurement facility.

The exact number of measurements used should be stated in the measurement report but only the mean or final declared value of the set is required to be included. Participants are reminded that the luminous intensity of the transfer standard lamps will change as a function of the operational burning time and so it is recommended that this is kept to a minimum.

The measurements should be taken at a sufficient large distance.

At BelGIM, all of the measurements will be carried out at the distance of 2 meters.

## 2.6.3 Geometrical conditions

- the optical axis of the bench is horizontal, perpendicular and central to the filament
- the distance is measured from the centre of the filament
- the plane, containing optical axis and lamp axis (cap down) is vertical
- only direct light is measured

## 2.6.4 Electrical conditions

All transfer standard lamps have to be operated with DC power where the lamp current is stabilized

## 2.6.5 Measurement instructions

Before connecting to any electrical power supply, the standard lamps should be inspected for damage or contamination of either the window of the lamp, the cap or its supporting mount. Any damage should be documented by photos and a drawing using the appropriate form in Annex D and the pilot laboratory should be informed immediately.

The operation time for each lamp is to be recorded using the form attached in the Annex G. This form should be completed and returned to the pilot laboratory as part of the Measurement report.

After connecting the electrical power to the lamps, the prescribed warm-up procedure for each lamp should be followed.

Operational parameters for each lamp (specified in the lamp operating procedure) should be recorded and compared to those supplied with the lamp.

The operational conditions and alignment procedure for each lamp should be noted and followed according to the details described in the notes supplied with each lamp. A photograph should be taken from the lamp installed and kept by the participants for documentation and quality insurance.

The photometric quantity (luminous intensity) of the transfer standards should then be measured together (at the same time if possible) with the electrical values.

The signed results of the measurements together with the operating condition (e.g. lamp number, current, voltage, distribution temperature) and the uncertainty ( $k=1$ ) have to be sent to Neutral Partner by FAX or regular mail. Electronic mail may be used additionally for convenience and rapid response.

The measured values of the operating conditions (especially current and distribution temperature) shall be displayed using an appropriate number of decimal places.

The transfer standards used in this comparison should not be used for any purpose other than described in this document nor given to any party other than the predetermined participants in the comparison.

## 3 Part II:

# Models for the Evaluation of Values, Uncertainties and Degrees of Equivalence

## 3.1 Principles

## 3.2 Measurement of Photometric Quantities

### 3.2.1 Fundamental Models for the Evaluation of Photometric Quantities

The transfer standards in the COOMET key comparisons of luminous intensity are given by the pilot laboratory.

Their relative spectral distributions  $S(\lambda)$  are similar to a Planckian radiator and characterized by distribution temperatures  $T_D$ .

For the measurement of luminous intensity  $I(T)$  the transfer standard and a photometer head are aligned to the optical axis of a photometer bench and located in a distance  $d$ , which is sufficiently large for a valid inverse squared law. The transfer standard illuminates the entrance aperture of a photometer head with the illuminance  $E(T)$ .

These definition lead to the fundamental measurement equation.

$$I(T) = d^2 \cdot E(T) \cdot \Omega_0^{-1} \quad (1)$$

### 3.2.2 Calibration of Photometric Quantities

The illuminances in these equations are measured as output signals of photometers with luminous responsivities and current-to-voltage converters with a gain setting resistor  $R_g$ . The photometer heads are matched to

$V(\lambda)$  with mismatch corrections  $F(S(\lambda))$  for any relative spectral distribution of the source.

Due to the (nearly) Planckian distributions  $P(\lambda, T)$ , of incandescent lamps used as transfer standards, an approximation  $F(P(\lambda, T)) \approx (T/T_A)^m$  is valid with an exponent

$m$ , de-noted as mismatch index, and the distribution temperature

$T_A = 2856$  K referring to CIE illuminant A (see Annex B).

$$E(T) = \frac{y}{R_g \cdot s_v} \left( \frac{T}{T_A} \right)^m \quad (2)$$

For a source based calibration the responsivity  $s_v$  in the equations is eliminated by substitution method using reference standards with properties similar to those of the transfer standards and referred by symbols marked with index "R".

$$I(T) = I_R(T_R) \cdot \frac{y \cdot R_{g,R}}{y_R \cdot R_g} \cdot \left(\frac{T}{T_R}\right)^m \cdot \left(\frac{d}{d_R}\right)^2 \cdot corr \quad (3)$$

### 3.3 Degrees of Equivalence

#### 3.2.1 Equivalence with KCRV

There are two statements on the Degree Of Equivalence (DOE): One defines the equivalence  $D_i$  of the values of one participant with the KCRV, the "reference value of a key comparison" and the other statement deals with the equivalence  $D_{ij}$  with the "value of a second participant".

The DOE  $D_i$  for the  $i$ -th participant with the (mean) value  $x_i$  of a quantity  $X$ , determined in a CCPR key comparison with reference value  $x_R$ , denoted as CCPR-KCRV is defined as the ratio of the two values subtracted by unity. The associated uncertainty  $u(D_i)$  is presented using the approximation  $x_i/x_R \approx 1$ .

$$D_i = \frac{x_i}{x_R} - 1; \quad u(D_i) \approx \sqrt{u_{rel}^2(x_i) + u_{rel}^2(x_R)} \quad (4)$$

The relative uncertainty, associated to CCPR-KCRVs of the key comparison of luminous intensity was found in Annex A to be negligible, if compared with the relative uncertainties associated to the values of all participants in these comparisons.

The values  $D_i$  with associated expanded uncertainties  $U(D_i) = 2u(D_i)$  are given in the BIPM-database and those of the two link partners in the COOMET key comparisons described in this report are shown in Table 1 using a percentage presentation.

Table 1

Measurand	VNIIOFI	SMU
Luminous Intensity	(0.33 ± 0.92)%	(-0.36 ± 1.40)%

For COOMET key comparisons (superscript «(m)») the related reference values  $x_R^{(m)}$ , denoted as RMO-KCRV, are evaluated by the pilot laboratory as a weighted mean of the values transferred from two link laboratories – VNIIOFI and SMU.

The DOE  $D_i$  of the luminous intensity measurement result, acquired by the participant laboratory of the CCPR key comparison, to the reference value of CCPR-KCRV is established by formula:

$$D_i = I_i / I_{CCPR} - 1 = C_i \quad (5)$$

Where  $I_i$  - the luminous intensity measurement result, acquired by the participant laboratory of the CCPR key comparison

$I_{CCPR}$  - the reference value of CCPR-KCRV.

The DOE  $D_{j^m}$  of the luminous intensity measurement result, acquired by the participant laboratory of the present comparison to the reference value of CCPR-KCRV is established by formula:

$$D_{j^m} = (I_j / I_i) \times (1 + C_i) - 1 \quad (6)$$

$I_j$  - the luminous intensity measurement result, acquired by the participant laboratory of the present comparison.

The combined uncertainty  $U_j$  is calculated by

$$U_j = 2\sqrt{u_i^2 + u_{i^m}^2 + u_{j^m}^2} \quad (7)$$

where  $u_i$  - the uncorrelated component of the standard uncertainty of the measurement result, acquired by the participant laboratory of CCPR key comparison;

$u_{i^m}$  - the uncorrelated component of the standard uncertainty of the measurement result, acquired by the participant laboratory of CCPR key comparison in present comparison;

$u_{j^m}$  - the standard uncertainty of the measurement result, acquired by the participant laboratory of present RMO comparison.



### 3.6 Literature

- [1] CCPR Key Comparison K3a of Luminous Intensity with Lamps as Transfer Standards; PTB-Opt-62; ISBN 3-89701-471-8
- [2] BIPM database: <http://kcdb.bipm.org/appendixB/default.asp>
- [3] Bilateral Comparison of Luminous Intensity and Luminous Responsivity Between CSIRO (Australia) and SPRING (Singapore)/ Final Report
- [4] *Mutual recognition arrangement: [BIPM - CIPM MRA](#)*
- [6] *Guide to the Expression of Uncertainty in Measurement (ISO)*

## Annex A: Degrees of equivalence with CCPR-KCRV

The degrees of equivalence for all participants in the CCPR key comparisons for luminous intensity copied from the BIPM-database [2].

### CCPR-K3.a and CCPR-K3.a.1

**MEASURAND: Luminous intensity**

The individual measurements,  $x_i$ , of the participating laboratories take the form of ratios which depend on the reference used at the pilot laboratory. This is cancelled out by normalization using the key comparison reference value,  $x_R$ . This procedure leads to normalized individual measurements:  $x_i / x_R$ .

- **Key comparison CCPR-K3.a**

The key comparison reference value,  $x_R$ , is calculated as the weighted average of the individual results  $x_i$ , weighted by the inverse square of the individual standard uncertainties,  $u_i$ , with the application of a minimum cutoff of 0.25%. The INI L and the BIPM are excluded from the calculation of  $x_R$ . The standard uncertainty of  $x_R$  is  $u_R = 0.09\%$ . It is negligible compared to the  $u_i$  values.

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms:  $D_i = (x_i - x_R) / x_R$  and  $U_i$ , its expanded uncertainty ( $k = 2$ ), both expressed in relative units.  $U_i = 2u_i$ .

The degree of equivalence between two laboratories is given by a pair of terms:  $D_{ij} = (x_i - x_j) / x_R$  and  $U_{ij}$ , its expanded uncertainty ( $k = 2$ ), both expressed in relative units.  $U_{ij} = 2(u_i^2 + u_j^2)^{1/2}$ .

- **Linking CCPR-K3.a.1 to CCPR-K3.a**

The link to the key comparison CCPR-K3.a is given by the pilot laboratory CSIRO-NML that participated in both comparisons. No new results are produced by the key comparison CCPR-K3.a.1 for the CSIRO-NML.

The degree of equivalence of SPRING Singapore relative to the CCPR-K3.a key comparison reference value is given by:  $D_{\text{SPRING Singapore}} = 0.0003$  and  $U_{\text{SPRING Singapore}} = 0.0033$ , see Section 9 of the [CCPR-K3.a.1 Final Report](#).

The degrees of equivalence between SPRING Singapore participant in CCPR-K3.a.1 and one laboratory participant in CCPR-K3.a are not calculated.

### CCPR-K3.a and CCPR-K3.a.1

**MEASURAND: Luminous intensity**

The following table displays the degrees of equivalence. It includes three parts:

- "white part", list of participants (Lab  $i$ );
- "blue part", degrees of equivalence relative to the key comparison reference value;
- "yellow part", degrees of equivalence between pairs of participants.

**The pair-wise degrees of equivalence are given as "Lab  $i$  - Lab  $j$ "**

Select Lab  $j$

Lab $i$	$D_i$	$U_i$	$D_{ij}$	$U_{ij}$
	/ 10 <sup>-2</sup>	/ 10 <sup>-2</sup>	/ 10 <sup>-2</sup>	/ 10 <sup>-2</sup>
<b>BNM-INM</b>	<b>0.89</b>	0.60	<b>0.59</b>	1.17
<b>CSIR-NML</b>	<b>0.51</b>	0.88	<b>0.21</b>	1.33
<b>CSIRO-NML</b>	<b>-0.07</b>	0.60	<b>-0.37</b>	1.17
<b>ETL</b>	<b>-0.09</b>	0.56	<b>-0.36</b>	1.15
<b>IEN</b>	<b>-0.43</b>	0.90	<b>-0.73</b>	1.35
<b>IFA</b>	<b>-0.48</b>	0.72	<b>-0.76</b>	1.23
<b>NIM*</b>	<b>-0.16</b>	0.48	<b>-0.46</b>	1.11
<b>NIST*</b>	<b>0.12</b>	0.48	<b>-0.18</b>	1.11
<b>NPL**</b>	<b>0.04</b>	0.30	<b>-0.26</b>	1.04
<b>NRC</b>	<b>0.19</b>	1.06	<b>-0.11</b>	1.46
<b>OFMET</b>	<b>-0.50</b>	1.12	<b>-0.80</b>	1.50
<b>OMH</b>	<b>0.05</b>	0.94	<b>-0.25</b>	1.37
<b>PTB*</b>	<b>-0.31</b>	0.40	<b>-0.61</b>	1.08
<b>SMU</b>	<b>-0.36</b>	1.40	<b>-0.66</b>	1.72
<b>VNIOFI</b>	<b>0.33</b>	0.92	<b>0.03</b>	1.36
<b>INTI**</b>	<b>-0.25</b>	0.74	<b>-0.55</b>	1.24
<b>BIPM**</b>	<b>0.30</b>	1.00		
<b>SPRING Singapore</b>	<b>0.03</b>	0.33	-	-

\*Cutoff uncertainty (0.25%) applied to those laboratory measurements in the calculation of the key comparison reference value,  $x_R$ .

\*\*Laboratory excluded from the calculation of  $x_R$ .

In **black**: SPRING Singapore participant in CCPR-K3.a.1 (also indicated with " in the Lab  $j$  list).

The full matrix of equivalence is available from [Summary Results](#) in a A4 printable format.

Unless otherwise stated, in the final numbers presented here, rounding has been applied according to ISO-31-0 Annex B Rule B.

## Annex B: Mismatch correction for Planckian radiators

The illuminance  $E(S(\lambda))$  is evaluated from photocurrent  $y$ , divided by the luminous responsivity  $s_v$  and multiplied with the mismatch correction factor  $F(S(\lambda))$ . The spectral responsivity  $s(\lambda) = s_0 \cdot s_{rel}(\lambda)$  of a photometer head can be written as product of a normalisation factor  $s_0$  and a relative spectral responsivity function  $s_{rel}(\lambda)$ , matched to  $V(\lambda)$ . The luminous responsivity  $s_v$  and mismatch correction  $F(S(\lambda))$  are evaluated from the relative function  $s_{rel}(\lambda)$  and are normalized using the Planckian distribution  $P(\lambda, T_A)$  for CIE illuminant A with the distribution temperature  $T_A = 2856$  K.

$$E(S(\lambda)) = \frac{y}{s_v} F(S(\lambda)), \quad \begin{cases} \frac{1}{s_v} = \frac{K_m}{s_0} \frac{\int P(\lambda, T_A) \cdot V(\lambda) d\lambda}{\int P(\lambda, T_A) \cdot s_{rel}(\lambda) d\lambda} \\ F(S(\lambda)) = \frac{\int S(\lambda) \cdot V(\lambda) d\lambda}{\int S(\lambda) \cdot s_{rel}(\lambda) d\lambda} \bigg/ \frac{\int P(\lambda, T_A) \cdot V(\lambda) d\lambda}{\int P(\lambda, T_A) \cdot s_{rel}(\lambda) d\lambda} \end{cases} \quad (A1)$$

The transfer standards in this report are incandescent lamps with relative spectral distributions  $S(\lambda)$ , similar to Planckian radiators  $P(\lambda, T)$ , characterised by a distribution temperature  $T$ . The mismatch correction from equ. (A1) with  $S(\lambda)$  replaced by  $P(\lambda, T)$  can be evaluated for several  $1 \leq i \leq n \leq 4$  distribution temperatures  $T$  and approximated by ratios  $T_i/T_A$  with a mismatch index  $m$  as exponent. The value of the mismatch index is determined by a least-mean-square fit.

$$\text{Min}_{m \rightarrow m} \sum_{i=1}^n \left[ F(P(\lambda, T_i)) - \left( \frac{T_i}{T_A} \right)^m \right]^2; \quad F(P(\lambda, T)) \approx \left( \frac{T}{T_A} \right)^m \quad (A2)$$

Luminous responsivity  $s_v$  and mismatch index  $m$  are characteristic quantities of a photometer. They can be determined from photometric measurements, too: A luminous intensity reference lamp (index "R") is operated (at least) at two luminous intensities  $I_{R1}(T_{R1}), I_{R2}(T_{R2})$  with distribution temperatures  $T_{R1}, T_{R2}$  and generates output signals  $y_{R1}, y_{R2}$ . From these values the characteristics can be evaluated.

$$m = \log \left( \frac{I_{R1}(T_{R1}) y_{R2}}{I_{R2}(T_{R2}) y_{R1}} \right) \bigg/ \log \left( \frac{T_{R1}}{T_{R2}} \right); \quad s_v = \frac{y_R \cdot d_R^2}{I_R(T_R)} \left( \frac{T_R}{T_A} \right)^m \quad (A3)$$

## Annex C: Origin of uncertainty contributions

Output signal: The output signal  $y$  of a photometer is determined from repeated readings  $\bar{y}$  corrected for a "dark signal"  $\bar{y}_0$ , a calibration factor  $c_y$  of the DVM and a relative stray light correction factor  $\gamma_y$  (No external light, only light of the standard is back reflected to the photometer).

The relative stray light factor  $\gamma_y$  is negligible, because the contributions are small

$\gamma_y \ll 1$ ;  $\gamma_{yR} \ll 1$ , and constant  $\gamma_y \cong \gamma_{yR}$  (assuming an unchanged field of view of the photometer). The dark signals are small if compared with the related output signal and (nearly) compensated due to the negative sign from the substitution method.

**Gain resistor:** The transfer and reference standard are often measured without a change of the gain resistor and the ratio  $R_{g,R}/R_g$  cancels out. Otherwise the ratio of the resistor values and the associated uncertainties has to be regarded as a factor with an associated relative uncertainty.

**Luminous responsivity:** The effective luminous responsivity  $s_v$  of a photometer head depends on the ambient temperature, the alignment and a possible aging, which can modify the value  $s_{v0}$ , found from former calibrations. In general a deviation  $\Delta T_s$  from the rated ambient temperature changes the responsivity with a relative temperature coefficient  $\alpha_s$ . The optical axis of the photometer bench should hit the centre of the entrance aperture rectangularly; any deviation by an angle  $\varepsilon_s$  changes the luminous responsivity with the cosine of that angle. The luminous responsivity of photometers is altered by aging with a relative aging coefficient  $\beta_s$  depending on the storage duration  $\Delta t_s$ , and higher order terms  $O(2)$  are omitted.

**Distance and radius:** On a photometer bench two reference planes are valid for the alignment of either lamps or photometers in a distance large enough to verify "point source behaviour" of the lamps. The effective distance  $d$  - is the sum of the distance  $d_B$  between the reference planes and possible offsets  $d_P, d_L$ , due to misalignments of photometer head and lamp, respectively.

A certificate for the length-meter states the calibration factor  $c_B$  for the operation at a specified ambient temperature. A deviation  $\Delta T_d$  changes the distance reading with the relative temperature coefficient  $\alpha_d$ . The alignment of lamps and photometer with respect to the reference planes is performed with zero offsets  $d_L = d_{LR} = d_P = 0$ , but with non-zero associated uncertainties  $u(d_L), u(d_{LR}), u(d_P)$ . In the inverse squared law the distance is squared and so the result is given with higher order terms omitted.

$$d^2 = c_d^2 \cdot d_B^2 \left( 1 + 2 \cdot \left( \frac{d_P + d_L}{d_B} + \alpha_d \cdot \Delta T_d \right) + O(2) \right) \quad (A4)$$

The substitution method at the pilot laboratory cancels out the calibration factor  $c_d$ . The

distance  $d_E$  is constant during a measurement campaign, so a possible offset  $d_P$  of the location of the photometer head cancels out and changes of the ambient temperature are negligible. The uncertainty of the lamps alignments has to be taken into account.

$$\left(\frac{d}{d_R}\right)^2 = \left(1 + 2\frac{d_L - d_{LR}}{d_B}\right) \quad (\text{A5})$$

**Electrical conditions:** An incandescent lamp operated at a rated lamp current  $J_A$  (nominal value without uncertainty) produces related values of luminous intensity  $I_A$ , distribution temperature  $T_A$  and lamp voltage  $U_A$  (in this document the character « $l$ » refers exclusively to the luminous intensity). A deviation of the lamp current to a near-by value  $J$  changes the related quantities by coefficients  $m_I = 7,0$ ;  $m_T = 0,7$ ;  $m_U = 1,9$  with the stated typical values.

$$I' = I \left(\frac{J}{J_A}\right)^{m_I}; \quad \Phi' = \Phi \left(\frac{J}{J_A}\right)^{m_I}; \quad T' = T \left(\frac{J}{J_A}\right)^{m_T}; \quad U' = U \left(\frac{J}{J_A}\right)^{m_U} \quad (\text{A6})$$

The luminous intensity may be corrected with the factor  $corr1$  for a precise setting of the lamp current using the exponent  $m_I$ . The mismatch correction deals with the distribution temperature, which is affected by the current setting, too. Finally, the correction including the mismatch reads:

$$\left(\frac{T}{T_R}\right)^m \text{corr1} = \left(\frac{J_{AR}}{J_A} \frac{J}{J_R}\right)^{-m_I} \left(\left(\frac{J_{AR}}{J_A} \frac{J}{J_R}\right)^{m_T}\right)^m = \left(\frac{J_{AR}}{J_A} \frac{J}{J_R}\right)^{m \cdot m_T - m_I} \quad (\text{A7})$$

The lamp current  $J$  is determined as mean value from repeated readings of the voltage drop  $\bar{U}_J$  across a shunt resistor. The voltage depends on the calibration factor  $c_J$  of the DVM and a possible offset voltage  $\bar{U}_{J0}$  in the electrical circuit. The shunt resistor  $R_0$  changes with the relative temperature coefficient  $\alpha_R$  for any deviation  $\Delta T_R$  from the rated ambient temperature or due to a temperature rise by the electrical power  $w R_0 J_A^2$  (thermal resistance  $w$  after thermal equilibrium).

$$\frac{J}{J_A} = \frac{c_J \bar{U}_J}{J_A R_0} \frac{1 - \bar{U}_{J0}/\bar{U}_J}{1 + \alpha_R (\Delta T_R + w \cdot R_0 \cdot J_A^2)} \quad (\text{A8})$$

At the pilot laboratory the currents of all transfer standards are measured with one shunt resistor and the effects of temperature variations and offset voltages  $\bar{U}_{J0}, \bar{U}_{J0R}$  are found to be negligible and the ratio of the measured lamp currents depends only on the voltage drop. The photometers are matched very close to  $V(\lambda)$  with a small mismatch index of about  $m = 0.01$ . In combination with equ. (A13) the correction of the electrical setting can be simplified using the relation  $|m| \cdot m_T \ll m_I$ .

$$\left(\frac{T}{T_R}\right)^m \text{corr1} = \left(\frac{J_{AR} \bar{U}_J}{J_A \bar{U}_{J,R}}\right)^{-m_1} \quad (\text{A9})$$

**Operational conditions:** The luminous intensity  $I$  of a transfer standard depends on the alignment. A relative alignment factor  $\gamma_L$  is determined for the individual type of lamps. It is averaged from repeated alignments of lamps of the same type as the transfer standards and it includes the effects of alignment with respect to the burning position as well as for the direction of emittance. A luminous intensity value may change by ageing from the duration  $\Delta t_L$  of all operations with a relative aging factor  $\beta_L$ , and the correction is applied individually for each lamp.

$$\frac{I(T)}{I_R(T_R)} \text{corr2} = \frac{I(T)}{I_R(T_R)} \frac{(1 + \beta_L \cdot \Delta t_L + \gamma_L + O(2))}{(1 + \beta_{LR} \cdot \Delta t_{LR} + \gamma_{LR} + O(2))} \quad (\text{A10})$$

At the pilot laboratory the luminous intensities are not affected by ageing of the transfer standards  $\beta_L \cdot \Delta t_L \ll 1$ , and only very little by alignment-errors due to camera-supported and documented alignments. Nevertheless, for luminous intensity transfer standards the alignment is a major contribution to the combined uncertainty, because the intensity varies strongly with small alignment errors.



## Annex E: Uncertainty budgets

**Model for Luminous Intensity:** The values of individual transfer standards of a batch are depending on the same (set) of reference standards, which creates correlated uncertainties.

This correlation is avoided, if the contributions in the evaluation are separated into two factors  $Y$  and  $Z$ , for individual or common effects, respectively.

$$I(T) = Y \cdot Z; \quad Y = \bar{y} \left( \frac{\bar{U}_J}{J_A} \right)^{-m_I} \left( 1 - \frac{\bar{y}_{0g}}{\bar{y}} + 2 \frac{d_L}{d_B} + \gamma_L \right) \quad (A11)$$

$$Z = \frac{I_R(T_R)}{\bar{y}_R} \left( \frac{J_{AR}}{\bar{U}_{J,R}} \right)^{-m_I} \left( 1 + \frac{\bar{y}_{0gR}}{\bar{y}_R} - 2 \frac{d_{LR}}{d_B} - \beta_{LR} \cdot \Delta t_{LR} \right)$$

$I(T)$  Luminous intensity value in a specified direction of a transfer standard, corrected for operational and ambient conditions and for the nominal DC-lamp current  $J_A$  and a related distribution temperature  $T$ . The value of this quantity is the result of the calibration procedure and the associated relative expanded uncertainties has to be determined.

$J_A; J_{AR}$  The values of the lamp currents are fixed to achieve specified values of luminous intensity and of distribution temperature. The values are stated as nominal values with neither an uncertainty nor a tolerance interval.

$I_R(T_R)$  Luminous intensity in specified direction of a reference standard as certified for operational conditions (current  $J_{AR}$ , and distribution temperature  $T_{AR}$ ) with associated standard uncertainties

$\bar{U}_J, \bar{U}_{JR}$  Mean values of 30 readings of the voltage drop across the shunt resistor. The empirical standard deviation of the means are taken as associated uncertainties (the resolution of the DVM was never limiting the standard deviation).

$\bar{y}, \bar{y}_0$  Mean values of 15 readings of the current-to-voltage converter output, when measuring the light of the transfer standard. The values depend on the range setting and are given for light and dark measurements together with the empirical standard deviations of the mean taken as standard uncertainty (the resolution of the DVM was sufficiently high and never limiting the standard deviation).

$\bar{y}_R, \bar{y}_{0R}$  Mean values of 15 readings of the current-to-voltage converter output, when measuring the light of the reference standard. The values depend on the range setting and are given for light and dark measurements together with the empirical

standard deviations of the mean taken as standard uncertainty (the resolution of the DVM was sufficiently high and never limiting the standard deviation).

- $d_B$  Distance is measured by an electronic translation meter with a resolution of  $\delta d_B = 5 \cdot 10^{-5}$  m, which is negligible, if compared to the certified interval of readings stated as expanded uncertainty  $U(d_B) = (0.0002 \pm 0.0001 \cdot d_B)$  m. The related standard uncertainty  $u(d_B) = (0.0001 + 0.00005 \cdot d_B)$  m is found after division by ( $k = 2$ ), which gives for  $d_B = 5.0$  m a standard uncertainty  $u(d_B) = 0.00035$  m.
- $d_L, d_{LR}$  Zero-values are adjusted for the distances, but the alignments are estimated as rectangular probability distributions and converted in a standard uncertainty. The estimations depend mainly on the images made by the camera-supported alignment system.
- $\gamma_L, \gamma_{LR}$  The angular alignment of unknown transfer standards is one of the most important contributions to the combined uncertainty associated to the luminous intensity. The coefficient is found from separate measurements of the intensity, when varying the alignment around a horizontal and a vertical axis through the centre of the filament, and the possible angles are estimated from the images.
- $\beta_L \cdot \Delta t_L$  The effect of aging is not important for transfer standards, because the duration of the operation is too short, it would be detected, when series of repeated measurements were carried out.
- $\beta_{LR} \cdot \Delta t_{LR}$  The effect of aging can become important for reference standards operated for a longer period of time. At BELGIM the reference standards are recalibrated annually within the network creating only small contribution to the uncertainty. In the comparison the transfer standards of the link partners eliminate any aging.
- $m, ml$  The mismatch index of a photometer can have a positive or a negative value and the associated uncertainty may be even larger than the value. At the BELGIM these values are well known and small  $|m| \approx 0.01$ . The other exponent, describing the variation of luminous intensity with a change of lamp current, is common to all incandescent lamps. The variation between different types of lamps may be included in the associated uncertainty interval.



## **Annex D: Inspection of the transfer standards**

**Has the lamp transportation package been opened during transit ? e.g. Customs...Y / N**

**If Yes please give details:**

**Is there any damage to the transportation package?.....Y / N.**

**If Yes please give details:**

**Are any fingerprints or contaminations visible indicating improper handling? .Y / N**

**If Yes give details:**

**Are there any visible signs of damage to the lamp or accessories?.....Y / N**

**If Yes please give details (e.g. scratches, dust, broken filament, alignment mask moved etc):**

**Do you believe the standard is functioning correctly ?...Y/ N**

**If not please indicate your concerns**

Operator:

Laboratory:

Date: Signature: .....

## **Annex E: Description of the measurement facility**

This form should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated, please use separate sheets of paper as appropriate.

**Make and type of the photometer (or equivalent)**

**Laboratory transfer standards used:**

**Description of measuring technique (please include a diagram):**

**Establishment or traceability route of primary scale including date of last realisation and breakdown of uncertainty:**

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

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

Operator:

Laboratory:

Date: Signature: .....

## Annex G: Record of lamp operating time

Lamp:

Date	Switch-on Local Time	Activity (Test, Alignment, Measure)	Switch-off Local Time	Burn Hrs	Operator initials

Operator:

Laboratory:

Date: Signature: .....

## Annex I: Receipt confirmation

**To: Olga Tarasova**

**„Belarussian State Institute of Metrology“ (BelGIM)**

**93, Starovilensky trakt, Minsk, 220053, Belarus**

**Fax + 375 17 288 09 38 Email: [khairova@belgim.by](mailto:khairova@belgim.by)**

### **From: Participating Laboratory**

We confirm having received the standards of the  
COOMET.PR-K3a Comparison of *Luminous Intensity*

After visual inspection

No damage has been noticed;

The following damage must be reported:

Operator:

Laboratory:

Date: Signature: .....