Final Report of the Key Comparison CCPR-K3.b.2-2004

Bilateral Comparison of Illuminance Responsivity Scales between the KRISS (Korea) and the HUT (Finland)

E. Ikonen and J. Hovila

Metrology Research Institute, Helsinki University of Technology (HUT), P.O. Box 3000, FIN-02015 HUT, Finland

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Abstract

A bilateral comparison of illuminance responsivity scales between the KRISS and the HUT was carried out, where the HUT acted as the pilot and link to the key comparison CCPR-K3.b. The ratio of the measured illuminance responsivities (KRISS/HUT) was 0.9982, with expanded uncertainty of 0.0060 (k = 2) including the uncertainty of the comparison and the uncertainties of the realization of the scales.

1. Introduction

At its meeting in 1997, the Consultative Committee for Photometry and Radiometry, CCPR, identified several key comparisons in the field of optical radiation metrology. One of those, illuminance responsivity, named CCPR-K3.b, has been carried out and its final report approved. In 2003, the Korea Research Institute of Standards and Science (KRISS) expressed the wish to repeat the exercise. The Helsinki University of Technology (HUT), Finland, accepted a subsequent bilateral comparison with the KRISS. The comparison was carried out according to a technical protocol approved in December 2003. This document reports the results of the bilateral comparison of illuminance responsivity between the HUT and the KRISS as a part of CCPR-K3.b.

2. Participants

The pilot of the comparison is Helsinki University of Technology, Finland. The participant of the comparison is Korea Research Institute of Standards and Science, Korea.

3. Comparison photometers

The KRISS supplied two transfer standard photometers for this comparison. The measurement artifacts consist of two LMT photometers with external aperture and a temperature controller unit (Fig. 1). The unit provides the current measurement port of the photometers. The same type of photometers has been used in the earlier key comparison of illuminance responsivity (CCPR-K3.b) [1] in almost similar conditions as for this comparison. The only difference is that the photometers in the present comparison have external apertures.

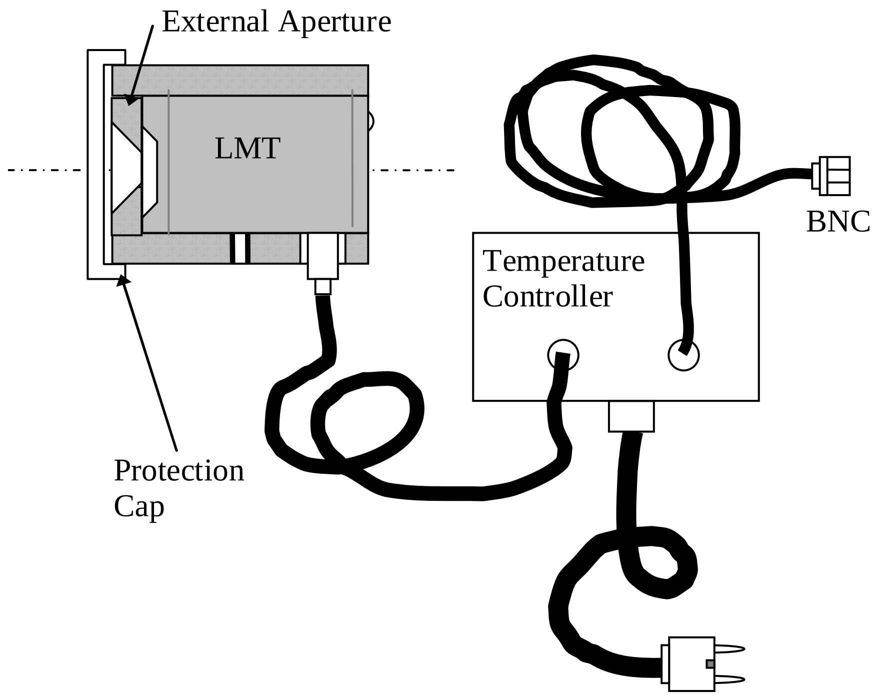

Figure 1. The transfer standard photometer housing and temperature controller. The orientation of the external aperture is reversed when measurements are started.

4. Protocol of the comparison

The form of the comparison was similar as that of the earlier comparison [1] although the present comparison was arranged as a bilateral comparison. The KRISS calibrated the photometers first and then sent them to the HUT with calibration results. The HUT calibrated the photometers and returned the devices. Finally, the KRISS recalibrated the photometers to check the drift during the comparison period and sent the results to the HUT. The HUT prepared the report of the comparison.

5. Comparison measurements and results

At the HUT, the transfer standard photometers were measured directly against the HUT reference photometer. The measurements were done at the illuminance level of approximately 50 lx and at a colour temperature of 2856 K using a luminous intensity standard lamp (Osram Wi/41G). The measurement setup and the reference photometer are described in more detail in Ref. [2]. The calibration results of the HUT are given in Table 1.

Table 1. The HUT calibration results of the transfer standard photometers.

Ambient temperature: 25.2 °C		
Artifact designation number	Illuminance responsivity (nA/lx)	Number of measurements
KTSP01	11.172	2
KTSP02	10.401	2

The calibration results of the KRISS are given in Tables 2 and 3. The measurements were carried out at the illuminance level of approximately 100 lx and at a colour temperature of 2856 K.

Table 2. The initial KRISS calibration results of the transfer standard photometers.

Ambient temperature: 22.5 °C		
Artifact designation number	Illuminance responsivity (nA/lx)	Number of measurement
KTSP01	11.153	4
KTSP02	10.381	4

Table 3. The KRISS calibration results after return of the transfer standard photometers.

Ambient temperature: 23.0 °C		
Artifact designation number	Illuminance responsivity (nA/lx)	Number of measurement
KTSP01	11.150	4
KTSP02	10.382	4

6. Measurement uncertainties

The uncertainty analysis is carried out in the same way as in an earlier informal bilateral comparison between the HUT and the NIST [3]. The uncertainty components of HUT calibration of the transfer standard photometers to the HUT illuminance responsivity scale are given in Table 4. The repeatability component includes effects due to photometer alignment and due to drift of the intensity of the lamp. The uncertainty for ensuring the same measurement positions for the reference photometer and for the transfer standard photometer was estimated to be ±0.5 mm, giving the distance setting uncertainty of Table 4. The current measurement uncertainty is caused by different gains of the current-to-voltage converter.

Table 4. HUT uncertainty budget for calibration to the HUT scale.

Component	Standard uncertainty (%)
Repeatability	0.03
Distance setting	0.02
Current measurement	0.01
Combined standard uncertainty	0.04

The uncertainty components of KRISS calibration of the transfer standard photometers to the KRISS scale of illuminance responsivity are given in Table 5. The component due to deviation from the reference color temperature is derived from the color temperature uncertainty of the lamp. The uncertainty from angular alignment and distance setting was obtained by repeating measurements after dispersing the setup so that it includes alignment variation as well as the effects due to drift of the intensity of the lamp.

Table 5. KRISS uncertainty budget for calibration to the KRISS scale.

Component	Standard uncertainty (%)
Deviation from the reference color temperature	0.02
Current measurement	0.02
Angular alignment and distance setting	0.07
Combined standard uncertainty	0.08

The uncertainty budget of the comparison is given in Table 6, where the first and third entries are taken from Tables 4 and 5, respectively. As the purpose of the present comparison is to establish a link to CCPR-K3.b, the uncertainty component due to seven-year stability of the HUT scale is taken into account as an uncertainty component of the comparison. From Ref. [2], a standard uncertainty of 0.04% over a time period of four years is obtained for the long-term stability of the HUT illuminance responsivity scale. This value is supported by results of earlier comparison measurements: The ratio of 1.0012 for the values of HUT illuminance responsivity measurements of years 2000 and 1997 can be calculated from the results of CCPR-K3.b [1] and the informal bilateral comparison with the NIST [3]. The combined standard uncertainty of this ratio is 0.0012, when combining quadratically the uncertainties of the comparisons and the HUT long-term stability component of Ref [2].

Table 6. Uncertainty budget for the illuminance responsivity comparison.

Component	Standard uncertainty (%)
HUT calibration of transfer photometers (to HUT scale)	0.04
Long-term stability of the HUT illuminance responsivity scale	0.07
KRISS calibration of transfer photometers (to KRISS scale)	0.08
Instability of transfer photometers during the comparison	0.01
Drift of the reference group of photometers at KRISS	0.03
Combined standard uncertainty of comparison	0.12

In Table 6, the uncertainty estimate due to instability of the transfer standard photometers during the comparison is based on the results of KRISS measurements (Tables 2 and 3). Before sending the photometers to the pilot laboratory, the illuminance scale contained in the transfer standard photometers was transferred to a reference group of photometers. After receiving the transfer standard photometers from the HUT, they were recalibrated at the KRISS against the reference group of photometers. The effect of different ambient temperatures at the HUT and KRISS was considered negligible, since the photometer temperature is controlled.

The uncertainty budget of the realization of illuminance responsivity scales is given in Table 7. This uncertainty budget is useful for assessing the agreement of the scale realizations through the uncertainty of the mutual degree of equivalence. The detailed uncertainty budgets of the realizations of the HUT and the KRISS are given in Appendix 1. At the HUT, the transfer standard photometers were compared directly with the reference photometer consisting of a characterized trap detector fitted with a $V(\lambda)$ filter and a precision aperture [2]. The trap responsivity is traceable to the HUT cryogenic radiometer. The KRISS reference photometer is also traceable to cryogenic radiometer.

Table 7. Uncertainties of the realizations of the illuminance responsivity scales.

Component	Standard uncertainty (%)
Uncertainty of the HUT illuminance responsivity scale	0.11
Uncertainty of the KRISS illuminance responsivity scale	0.25
Combined standard uncertainty of realization of the scales	0.27

7. **Ratios of the KRISS data to the HUT data**

Ratios of the illuminance responsivities measured by the KRISS and the HUT are given in Table 8. Average values of the KRISS data of Tables 2 and 3 are used.

Table 8. Ratios of the illuminance responsivities measured by the KRISS and the HUT

Artifact designation number	Ratio (average KRISS)/HUT	Standard uncertainty
KTSP01	0.9982	0.0012
KTSP02	0.9981	0.0012
Average	0.9982	0.0012

The standard uncertainty of the ratios is the combined standard uncertainty of the comparison from Table 6 and is valid when comparing the present KRISS scale with the HUT scale of 1997. The discrepancy of the illuminance responsivity scales realized by the HUT and the KRISS is well within the combined standard uncertainty of 0.0030, calculated as the quadratic sum of the combined standard uncertainties of Tables 6 and 7.

References

[1]. R. Köhler, M. Stock, and C. Garreau, Final Report on the International Comparison of Luminous Responsivity CCPR-K3.b (2004).

[2.] P. Toivanen, P. Kärhä, F. Manoochehri, and E. Ikonen, Realization of the Unit of Luminous Intensity at the HUT, *Metrologia* **37**, 131-140 (2000).

[3.] J. Hovila, P. Toivanen, E. Ikonen, and Y. Ohno, International Comparison of the Illuminance Responsivity Scales and Units of Luminous Flux Maintained at the HUT (Finland) and the NIST (USA), *Metrologia* **39**, 219-223 (2002).

Appendix 1 – Detailed uncertainty budgets

The detailed updated uncertainty budget of the HUT illuminance responsivity scale is given below. Most of the components are similar to those of Ref. [2].

Component (HUT)	$10^4 \times$ standard uncertainty
Detector	
Absolute responsivity	3.3
Non-linearity	1.2
Spatial non-uniformity	1.2
Photocurrent measurement	1.1
Filter	
Peak transmittance	6.0
Spatial non-uniformity	4.4
Angular dependence of transmittance	0.5
Temperature setting	1.7
Polarization dependence of transmittance	0.6
Out-of-band leakage	2.0
Color-correction factor	
Spectral responsivity of the trap detector	1.0
Spectral transmittance of the filter	2.1
Angular dependence of the spectral transmittance	0.7
Temperature dependence of the spectral transmittance	0.3
Spectrum of the lamp	1.1
Aperture area	5.0
Inter-reflections in the photometer	0.9
Measurement related	
Operating current of the lamp	0.1
Distance measurement (2500 mm)	1.4
Stray light	1.0
Repeatability of the alignment	1.0
Diffraction	1.0
Combined standard uncertainty (HUT)	11

The detailed uncertainty budget of the KRISS illuminance responsivity scale is given below.

Component (KRISS)	$10^4 \times$ standard uncertainty
Photometer (LMT)	
Absolute responsivity at 555 nm	19
Non-linearity	3
Spatial non-uniformity	3
Photocurrent measurement	2
Color-correction factor	
Wavelength scale of responsivity comparator	11
Repeatability of relative responsivity	5
Calculation of color-correction factor	2
Out-of-band leakage	3
Aperture area	5
Inter-reflections in the photometer	1
Measurement related	
Color temperature of lamp	2
Operating current of the lamp	1
Distance measurement	2
Stray light	2
Repeatability of angular alignment and distance setting	7
Combined standard uncertainty (KRISS)	25

Appendix 2 - Link to the key comparison CCPR-K3.b

The link of the comparison result to the key comparison CCPR-K3.b is considered in this Appendix. The relative deviation of the HUT result from the key comparison reference value is [1]

$$d(\mathrm{HUT}) = -0.0035 \pm 0.0011, \quad (1)$$

where the standard uncertainty of 0.0011 includes only the uncertainty of the comparison and the uncertainty of the key comparison reference value.

Combining the results of Eq. (1) and of Tables 7 and 8, the degree of equivalence of the KRISS in CCPR-K3.b is given by

$$D(\mathrm{KRISS}) = -0.0053 \pm 0.0060, \quad (2)$$

where the expanded uncertainty of 0.0060 (k = 2) is calculated as twice the quadratic sum of the uncertainties of the KRISS illuminance responsivity scale (Table 7), of Table 8, and of Eq. (1).

With the values of Eq. (2) and those reported in Ref. [1], the mutual degrees of equivalence between the KRISS and participants of CCPR-K3.b can be calculated in a straightforward way. For example, the mutual degree of equivalence between the KRISS and the HUT is

$$D(\mathrm{KRISS, HUT}) = -0.0018 \pm 0.0087, \quad (3)$$

where the expanded uncertainty of 0.0087 (k = 2) is calculated as the quadratic sum of the uncertainty of Eq. (2), of the expanded calibration uncertainty of the HUT result in CCPR-K3.b, and of the expanded uncertainty of comparison CCPR-K3.b.

The mutual degrees of equivalence between the KRISS and the participants of CCPR-K3.b are given below:

NMI	*D*(KRISS, NMI)	*U*(KRISS, NMI) (*k* = 2)
BNM-INM	0.0027	0.0084
IFA	-0.0091	0.0087
CSIRO-NML	-0.0062	0.0072
HUT	-0.0018	0.0087
MSL	0.0028	0.0080
NIM	-0.0066	0.0067
NIST	-0.0038	0.0074
NPL	-0.0050	0.0072
NRC	-0.0053	0.0118
METAS	-0.0155	0.0080
OMH	-0.0016	0.0084
PTB	-0.0088	0.0071
SMU	-0.0029	0.0166
VNIIOFI	-0.0083	0.0079
BIPM	-0.0037	0.0080