

APMP Supplementary Comparisons of LED Measurements

APMP.PR-S3a Averaged LED Intensity

APMP.PR-S3b Total Luminous Flux of LEDs

APMP.PR-S3c Emitted Colour of LEDs

Final Report (July 2012)

Dong-Hoon Lee, Seongchong Park, and Seung-Nam Park

Division of Physical Metrology, Korea Research Institute of Standards and Science (KRISS)

267 Gajeong-Ro, Yuseong-Gu, Daejeon 305-340, Rep. Korea

Correspondance to: dh.lee@kriss.re.kr

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1. Introduction

With the recent growth of the solid state lighting and display industry, the interest and importance of accurate measurement of light-emitting diodes (LEDs) are increasing. Photometric measurement of LEDs, however, is influenced by the specific properties of individual LED such as spectral distribution, spatial emission profile, temperature dependence, etc. In general, the measurement uncertainty of LEDs is larger than that of the conventional incandescent lamps, and greater care is required to avoid or correct the systematic errors related to the LED properties.

The Asia Pacific Metrology Programme (APMP) Technical Committee of Photometry and Radiometry (TCP/R) decided at its meeting in December 2006 to conduct supplementary comparisons on measurement of LEDs to test the metrological equivalence among national metrology institutes (NMIs) under the CIPM Mutual Recognition Arrangement (MRA)¹. The participation was not limited to NMIs in APMP, but also NMIs of other regional metrology organizations (RMOs). The Korea Research Institute of Standards and Science (KRISS) of Republic Korea is designated as the pilot laboratory.

Three measurement quantities of LEDs are selected for the comparisons, which are listed as service categories for Calibration and Measurement Capabilities (CMCs): averaged LED intensity in condition B defined by International Commission on Illumination (CIE)², total luminous flux, and emitted color expressed as chromaticity coordinates (x, y) according to the CIE 1931 standard colorimetric system³. The three comparisons are registered as APMP:PR-S3a, -S3b, and -S3c, respectively.

In this report, we summarize the results of the comparison S3c on emitted color of LEDs.

2. Comparison Protocol

The organization, the artifact LEDs, and the guidelines for measurement and report of all the three comparisons (S3a, S3b, S3c) are settled on one technical protocol before the start of the comparisons. The protocol is drafted by the pilot lab, agreed by the participants, and approved by the APMP TCP/R in January 2008. The protocol is once revised in November 2008, as the INM of Romania has joined as an additional participant.

¹ <http://www.bipm.org/en/cipm-mra/>

² Measurement of LEDs, 2nd edition, CIE Technical Report 127-2007.

³ Colorimetry, 3rd edition, CIE 015:2004.

The final version of the technical protocol is included in

Table 10-1. Summary of the unilateral DoEs and their uncertainties for APMP.PR-S3c chromaticity coordinate x (temperature correction applied).

NMI	RED		GREEN		BLUE		WHITE		DIFFUSE	
	DoE (x)	U of DoE	DoE (x)	U of DoE	DoE (x)	U of DoE	DoE (x)	U of DoE	DoE (x)	U of DoE
MIKES	0.0011	0.0039	0.0005	0.0064	-0.0007	0.0022	0.0020	0.0110	0.0022	0.0138
CMS-ITRI	0.0001	0.0041	0.0042	0.0068	-0.0026	0.0036	0.0001	0.0068	0.0064	0.0206
PTB	0.0009	0.0033	0.0005	0.0064	-0.0002	0.0019	0.0005	0.0034	0.0008	0.0053
NMIJ	0.0009	0.0034	0.0000	0.0063	0.0000	0.0019	-0.0030	0.0048	0.0018	0.0054
CENAM	-0.1059	0.0136	0.0277	0.0059	0.0129	0.0033	0.0058	0.0026	0.0521	0.0079
LNE	0.0003	0.0077	-0.0007	0.0063	0.0000	0.0023	0.0002	0.0067	N.A.	N.A.
METAS	0.0013	0.0032	0.0011	0.0050	-0.0001	0.0018	-0.0003	0.0049	0.0012	0.0066
NMC-A*STAR	0.0014	0.0032	-0.0037	0.0054	-0.0009	0.0018	-0.0003	0.0030	-0.0037	0.0053
NMIA	-0.0091	0.0036	-0.0034	0.0053	0.0024	0.0019	-0.0061	0.0040	-0.0024	0.0052
NIST	0.0010	0.0032	-0.0001	0.0060	-0.0004	0.0018	0.0010	0.0027	0.0003	0.0049
VNIOFI	0.0007	0.0036	0.0034	0.0053	-0.0018	0.0025	-0.0001	0.0028	0.0044	0.0057
MKEH	0.0006	0.0037	0.0040	0.0052	0.0005	0.0022	-0.0084	0.0047	0.0028	0.0069
INM	0.0015	0.0042	-0.0018	0.0054	-0.0006	0.0028	-0.0064	0.0054	-0.0002	0.0052
KRISS	-0.0007	0.0030	-0.0026	0.0047	0.0014	0.0017	0.0005	0.0013	-0.0030	0.0047

Table 10-2. Summary of the unilateral DoEs and their uncertainties for APMP.PR-S3c chromaticity coordinate y (temperature correction applied).

NMI	RED		GREEN		BLUE		WHITE		DIFFUSE	
	DoE (y)	U of DoE	DoE (y)	U of DoE	DoE (y)	U of DoE	DoE (y)	U of DoE	DoE (y)	U of DoE
MIKES	-0.0004	0.0017	0.0004	0.0047	0.0004	0.0042	0.0026	0.0165	-0.0012	0.0148
CMS-ITRI	0.0003	0.0046	0.0029	0.0073	0.0045	0.0060	0.0020	0.0065	0.0025	0.0191
PTB	-0.0002	0.0016	0.0000	0.0061	-0.0003	0.0040	0.0013	0.0037	-0.0009	0.0062
NMIJ	-0.0002	0.0015	0.0002	0.0052	0.0004	0.0041	-0.0013	0.0049	-0.0041	0.0066
CENAM	0.0088	0.0024	-0.0698	0.0083	0.0017	0.0049	-0.0093	0.0028	-0.1440	0.0174
LNE	0.0004	0.0033	-0.0009	0.0085	-0.0015	0.0053	0.0009	0.0095	N.A.	N.A.
METAS	-0.0005	0.0014	-0.0003	0.0045	0.0017	0.0038	0.0010	0.0054	0.0002	0.0077

NMC-A*STAR	-0.0005	0.0014	0.0087	0.0054	0.0007	0.0040	0.0015	0.0036	0.0095	0.0058
NMIA	0.0004	0.0016	-0.0072	0.0052	-0.0051	0.0037	-0.0038	0.0039	-0.0017	0.0050
NIST	-0.0001	0.0014	0.0006	0.0052	-0.0005	0.0037	0.0022	0.0025	-0.0002	0.0055
VNIIOFI	-0.0004	0.0022	0.0005	0.0049	0.0036	0.0042	0.0025	0.0027	-0.0019	0.0065
MKEH	0.0002	0.0022	-0.0001	0.0046	0.0025	0.0040	-0.0033	0.0043	0.0005	0.0072
INM	-0.0012	0.0031	0.0026	0.0049	0.0000	0.0043	-0.0081	0.0058	0.0028	0.0055
KRISS	0.0013	0.0013	-0.0046	0.0043	-0.0031	0.0036	0.0020	0.0013	-0.0030	0.0042

Acknowledgement

The pilot work of this comparison is partly supported by the Korean Ministry of Knowledge and Economy under the project of LED standardization, grant B0010209.

Appendix A: Technical Protocol as an electronic file. Table 0-1 shows the final list of participants to the S3c comparison with the measurement schedules planned and performed. We note that the NPL of the UK listed on the technical protocol has withdrawn its participation in August 2009.

Table 0-1. List of participants and measurement schedules of APMP.PR-S3a.

NMI	country	contact person(s)	measurement planned	LED set	measurement performed	results reported
KRISS (pilot)	Korea	Seongchong Park, Dong-Hoon Lee	--	--	--	--
NMC-A*STAR	Singapore	Yuanjie Liu, Gan Xu	June ~ Aug. 2008	#8	10 July ~ 28 Aug. 2008	12 Jan. 2009
MIKES	Finland	(Pasi Manninen), Tuomas Poikonen,	March ~ May 2008	#1	7 April ~ 13 April 2008	17 June 2008
NIST	USA	Cameron Miller, Yoshi Ohno, Yuqin Zong	Aug. ~ Oct. 2008	#3	18 Feb. ~ 25 Feb. 2009	31 July 2009
CMS-ITRI	Chinese Taipei	Cheng-Hsien Chen	March ~ May 2008	#2	26 May 2008 ~ 2 Oct. 2009*	26 Oct 2009
PTB	Germany	Matthias Lindemann, Robert Maass	April ~ June 2008	#3	May ~ July 2008	18 July 2009
CENAM	Mexico	Laura P. González, Anayansi Estrada, Eric Rosas	May ~ July 2008	#5	17 July ~ 21 July 2008	08 May 2009
NMIJ	Japan	Kenji Godo, (Terubumi Saito)	April ~ June 2008	#4	17 April ~ 22 June 2008	01 Aug. 2008
METAS	Switzerland	Peter Blattner	June ~ Aug. 2008	#7	08 Sept ~ 17 Sept 2008	07 April 2009
LNE	France	Jimmy Dubard	May ~ July 2008	#6	15 June ~ 13 July 2008	15 April 2009
NMIA	Australia	(Philip Lukins), Peter Manson	July ~ Sept. 2008	#2	Jan. ~ May 2009	4 May 2010
VNIIOFI	Russia	Tatiana Gorshkova, Stanislav Shirokov	Sept. ~ Nov. 2008	#5	28 Nov ~ 05 Dec 2008	06 Feb. 2009
MKEH	Hungary	George Andor	Sept. ~ Nov. 2008	#6	20 Nov ~ 09 Dec 2008	25 March 2009
INM	Romania	Mihai Simionescu	Nov. ~ Dec. 2008	#7	Dec 2008	30 March 2009

* The CMS-ITRI had the initial measurement in May 2008, but it had to repeat the measurement on the red LEDs in Oct 2009 due to damages in the initial measurement.

The comparison was performed as a star-type circulation of multiple sets of artifact LEDs. The round for each participant had the following sequence: (1) first measurement by the pilot, (2) measurement by the participant, (3) second measurement by the pilot. The results of the repeated measurement by the pilot are used to evaluate the stability of the artifact LEDs.

3. Artifact LEDs

Five different types of LEDs are used as comparison artifacts: RED (Nichia model NSPR518S), GREEN (Nichia model NSPG518S), BLUE (Nichia model NSPB518S), WHITE (Nichia model NSPW515BS), and DIFFUSER-TYPE GREEN (NSPG518S mounted in a cylinder-type cap with an opal diffuser). All the bare LEDs had a lamp diameter of 5 mm and were to be operated at a forward direct current of 20 mA. The detailed information of the LEDs is included in the technical protocol (Appendix A).

Each set of artifact LEDs consisted of three pieces of the red (R), green (G), blue (B), and white (W) LEDs and two pieces of the diffuser-type green (D) LEDs. They were packaged and identified as shown in Fig. 3-1. The pilot prepared eight sets of artifact LEDs for the LED comparisons S3a, S3b, and S3c. Each artifact LED is designated in a form #N-X-M with three codes:

- #N as the artifact set number: N = 1, 2, ..., 8
- X as LED color and type code: X = R for red, G for green, B for blue, W for white, D for diffuser-type green
- M as sample serial number for each type: M = 1, 2, 3

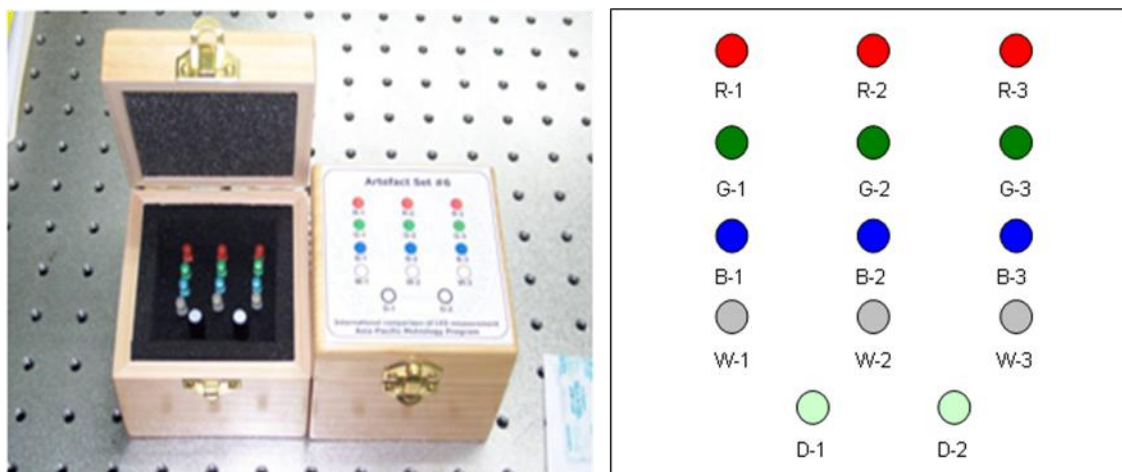


Fig. 3-1. Artifact LED set circulated in the LED comparisons S3a, S3b, and S3c.

The artifact LEDs are prepared based on the functional seasoning⁴ that records during the pre-burning the relative change of luminous intensity and spectral distribution

⁴ Seongchong Park *et al.*, Metrologia 43, 299 (2006).

of each individual LED together with its junction voltage under the ambient temperature periodically varied from 18 °C to 33 °C. From the recorded data, the temporal drift and the temperature dependence of the optical characteristics of each LED could be separately determined. Each artifact LEDs has passed a seasoning procedure over 300 hours.

Since the photometric properties of LEDs have a very high dependence upon temperature, their comparison requires a sensitive control or monitoring of the junction temperature. As the junction voltage V_j of a LED can be approximated as a linear function of the junction temperature T in a small interval, say ± 10 °C, around a reference temperature of T_0 ,⁵ we can model the temperature dependence of the chromaticity coordinates x and y of a LED as a second-order polynomial with three coefficients:

$$\begin{aligned} x(T) - x(T_0) &\approx a_x [V_j(T) - V_j(T_0)] \\ y(T) - y(T_0) &\approx a_y [V_j(T) - V_j(T_0)] \end{aligned} \quad (3-1)$$

Note that differently from the quantities such as averaged LED intensity or luminous flux⁶, the dependence of the chromaticity coordinates on temperature was small enough so that a single-parameter additive model was sufficient to describe it. The coefficients a_x and a_y of each artifact LED could be determined by fitting the function of Eq. (3-1) to the functional seasoning data. With these results, the pilot was capable to calculate a temperature correction factor for the measurement result of any artifact LED to the same measurement condition, as long as the junction voltage at the time of measurement is known. The uncertainty of this correction factor is estimated from the goodness of fit for the coefficients for each artifact LED.

In the comparison S3c, the measurement condition was specified with an ambient temperature of 25 °C. In addition, the junction voltage of each LED was to be recorded to monitor the junction temperature and to apply the aforementioned temperature correction. In the chapters 7~9, we will show and discuss this effect of the temperature correction to the comparison results.

⁵ See, for example, E. F. Schubert, *Light-Emitting Diodes* (Cambridge University Press, 2003)

⁶ Final reports of APMP:PR-S3a and -S3b

4. Measurement Capabilities of Participants

In this chapter, we summarize the information on measurement capabilities and uncertainty budgets for emitted color of LEDs, which are reported by each participant.

4.1. KRISS

4.1.1. Measurement setup

오류! 참조 원본을 찾을 수 없습니다. shows the measurement setup of emission color measurement in the geometrical condition of the CIE-B averaged LED intensity. We use a CCD-mounted spectrograph-type spectroradiometer (CAS140CT-153 made by Instrument Systems), of which the input optics is composed of a 1.5" integrating sphere and fiber bundle. The aperture area of the integrating sphere is 1 cm². It covers 380 nm to 1050 nm, and its spectral bandwidth (FWHM) is about 3 nm at 633 nm. The detector holder is mounted on a 5-axis stage.

The LED is driven by a source-meter unit (2400 Sourcemeter made by Keithley), which provides both of current sourcing and voltage measuring function. The DUT LED is connected to the source-meter unit using 4-wire connection. As shown in **오류! 참조 원본을 찾을 수 없습니다.** and **오류! 참조 원본을 찾을 수 없습니다.**, the LED socket is cone-shaped and mounted on a 5-axis stage, which provides 4-wire electrical contacts to the LED.

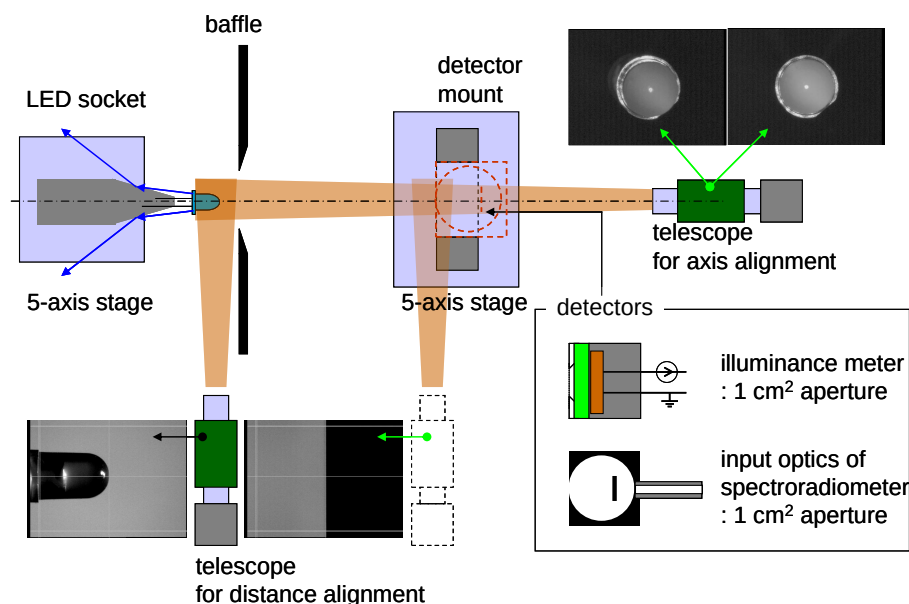


Fig. 4-1. LED emission color measurement setup in KRISS.

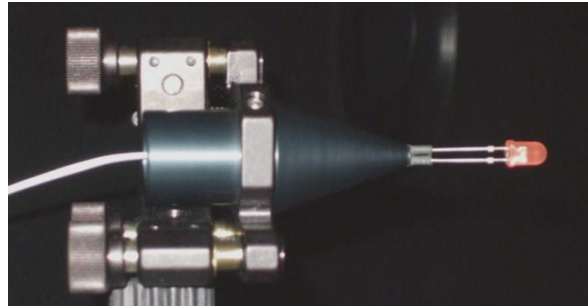


Fig. 4-2. LED Measurement socket in KRIS.

4.1.2. Mounting and alignment

As shown in Fig. 4-1, there are two 5-axis stages and two telescope cameras. Using an alignment laser and a couple of centring jigs (made of a precision reticule), the axis of the optical bench is aligned, and successively the cameras position and tilt are adjusted. One telescope camera is for distance alignment between the LED tip and the detector aperture, and the other for axis alignment of the LED. 오류! 참조 원본을 찾을 수 없습니다. and 오류! 참조 원본을 찾을 수 없습니다. show how we align the LED axis and the distance of LED tip to detector aperture.

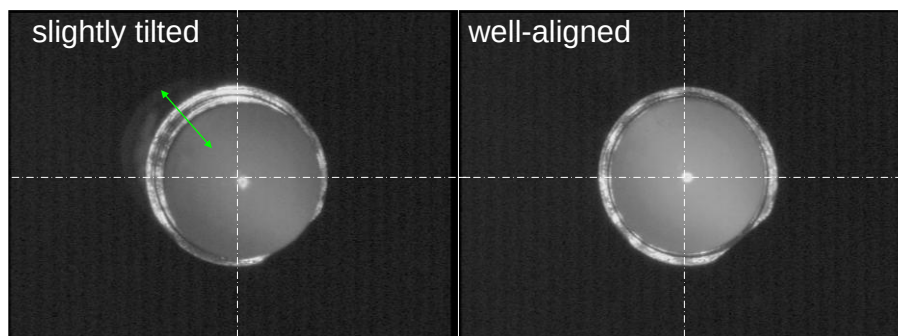


Fig. 4-3. Axis alignment in KRIS.

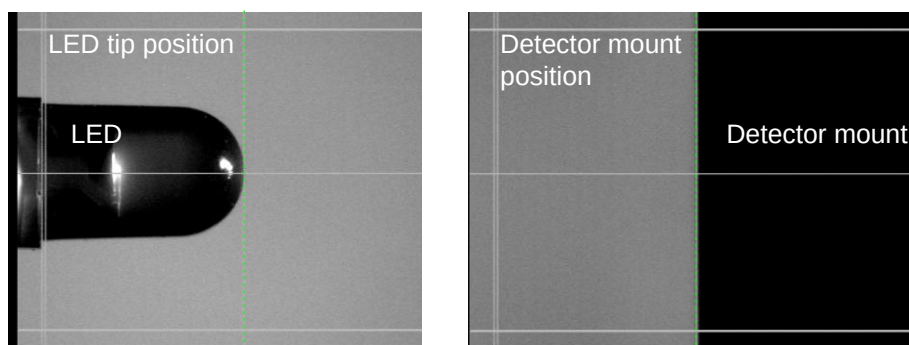


Fig. 4-4. Distance alignment in KRIS.

4.1.3. Traceability

For the spectroradiometer, the relative spectral responsivity is calibrated using a spectral irradiance standard lamp traceable to NIST spectral irradiance scale.

4.1.4. Measurement uncertainty

Tables in the following show the detailed uncertainty budgets of the emission color (CIE 1931 x, y chromaticity) for the LEDs used in this APMP LED comparison. The uncertainty evaluation is carried out according to Guide to the Expression of Uncertainty in Measurement (GUM). Expanded uncertainty are evaluated at a confidence level of approximately 95% with a coverage factor normally $k = 2$. 오류! 참조 원본을 찾을 수 없습니다. is the detailed uncertainty budget of the junction voltage measurement.

**Table 4-1. KRISS uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R).
Upper values for x, lower values for y.**

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	DoF	Correlated?
repeatability	0.00001 0.00001	A	t	1	0.00001 0.00001	9	N
axis alignment	0.00004 0.00002	B	rectangular	1	0.00004 0.00002	∞	N
current feeding	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	Y
distance setting	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	N
linearity	0.00001 0.00001	B	normal	1	0.00001 0.00001	∞	N
spectral stray light	0.00148 0.00025	B	normal	1	0.00148 0.00025	∞	Y
instrument calibration	0.00002 0.00002	B	normal	1	0.00002 0.00002	∞	Y
wavelength accuracy	0.00062 0.00064	B	normal	1	0.00062 0.00064	∞	Y
Combined standard uncertainty			normal		0.0016 0.0007	>10 >10	

Table 4-2. KRISS uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	DoF	Correlated?
repeatability	0.00001 0.00001	A	t	1	0.00001 0.00001	9	N

axis alignment	0.00003 0.00007	B	rectangular	1	0.00003 0.00007	∞	N
current feeding	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	Y
distance setting	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	N
linearity	0.00003 0.00003	B	normal	1	0.00003 0.00003	∞	N
spectral stray light	0.00044 0.00201	B	normal	1	0.00044 0.00201	∞	Y
instrument calibration	0.00013 0.00009	B	normal	1	0.00013 0.00009	∞	Y
wavelength accuracy	0.00240 0.00108	B	normal	1	0.00240 0.00108	∞	Y
Combined standard uncertainty			normal		0.0025 0.0023	>10 >10	

Table 4-3. KRISS uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	DoF	Correlated?
repeatability	0.00001 0.00003	A	t	1	0.00001 0.00003	9	N
axis alignment	0.00001 0.00002	B	rectangular	1	0.00001 0.00002	∞	N
current feeding	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	Y
distance setting	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	N
linearity	0.00001 0.00001	B	normal	1	0.00001 0.00001	∞	N
spectral stray light	0.00032 0.00031	B	normal	1	0.00032 0.00031	∞	Y
instrument calibration	0.00003 0.00009	B	normal	1	0.00003 0.00009	∞	Y
wavelength accuracy	0.00079 0.00187	B	normal	1	0.00079 0.00187	∞	Y
Combined standard uncertainty			normal		0.0009 0.0019	>10 >10	

Table 4-4. KRISS uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	DoF	Correlated?
repeatability	0.00001 0.00009	A	t	1	0.00001 0.00009	9	N
axis alignment	0.00008 0.00012	B	rectangular	1	0.00008 0.00012	∞	N

current feeding	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	Y
distance setting	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	N
linearity	0.00004 0.00005	B	normal	1	0.00004 0.00005	∞	N
spectral stray light	0.00010 0.00006	B	normal	1	0.00010 0.00006	∞	Y
instrument calibration	0.00048 0.00061	B	normal	1	0.00048 0.00061	∞	Y
wavelength accuracy	0.00053 0.00049	B	normal	1	0.00053 0.00049	∞	Y
Combined standard uncertainty			normal		0.0008 0.0008	>10 >10	

Table 4-5. KRISS uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	DoF	Correlated?
repeatability	0.00005 0.00013	A	t	1	0.00005 0.00013	9	N
axis alignment	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	N
current feeding	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	Y
distance setting	0.00001 0.00001	B	rectangular	1	0.00001 0.00001	∞	N
linearity	0.00003 0.00003	B	normal	1	0.00003 0.00003	∞	N
spectral stray light	0.00044 0.00201	B	normal	1	0.00044 0.00201	∞	Y
instrument calibration	0.00013 0.00009	B	normal	1	0.00013 0.00009	∞	Y
wavelength accuracy	0.00240 0.00108	B	normal	1	0.00240 0.00108	∞	Y
Combined standard uncertainty			normal		0.0025 0.0023	>10 >10	

Table 4-6. KRISS uncertainty budget of junction voltage measurement.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (mV)	DoF	Correlated?
sourcemeter calibration	0.05 mV	B	normal	1	0.05	∞	Y
sourcemeter offset	0.10 mV	B	normal	1	0.10	∞	Y
repeatability	0.04 mV	A	t	1	0.04	9	N
stray resistance	0.02 mV	B	rectangular	1	0.02	∞	Y
Combined standard uncertainty			normal		0.12	>20	

nty (mV)							
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4.2. MIKES

4.2.1. Measurement setup

A spectroradiometer, which was used for spectral measurement of LEDs, was of type DM150 from Bentham Inc. The spectroradiometer included a diffuser of type Bentham D7, 1-m optical fiber, a monochromator and a photomultiplier tube (PMT) with a temperature sensor. The photocurrent from the PMT was measured using a specific amplifier and data-acquisition system made by the Bentham.

The relative spectral power distributions of the LEDs were measured with a bandwidth of 1 nm by the 1-nm step within a range of 380-780 nm. The solid angle of the measurement, 0.01 sr, was obtained by setting the receiving aperture plane of the diffuser to a distance of 50.7 mm from the front tip of the LED when the radius of the optical receiving aperture of the diffuser was 2.9 mm. The chromaticity coordinates (x, y) of the LEDs were calculated using the color matching functions of the CIE1931 2° standard colorimetric observer. During the measurements, the ambient temperature was $(21.5 \pm 1.0) ^\circ\text{C}$ and the relative humidity of air was $(31 \pm 5) \%$.

4.2.2. Mounting and alignment

The diffuser of the spectroradiometer and LED holder were mounted to the measurement rail. The LED to be calibrated was mounted onto the optical table using x-y translator, rotary stage, and tilt stage. The diffuser was mounted onto the rail carrier using a magnetic base plate and tilt stages. The spectroradiometer and LED under calibration were mounted onto the same optical axis using a two-beam alignment laser. The spectroradiometer was aligned using an auxiliary mirror to get the back-reflection into the alignment laser. Translational alignment of the LEDs was made by an x-y translator so that the laser beam hit the front tip of the LED. Angular alignment of the LEDs was made by a digital camera, rotary stage, and tilt stage. The distance from the front tip of the LED to the entrance aperture of the diffuser was measured using magnetic measurement rail.

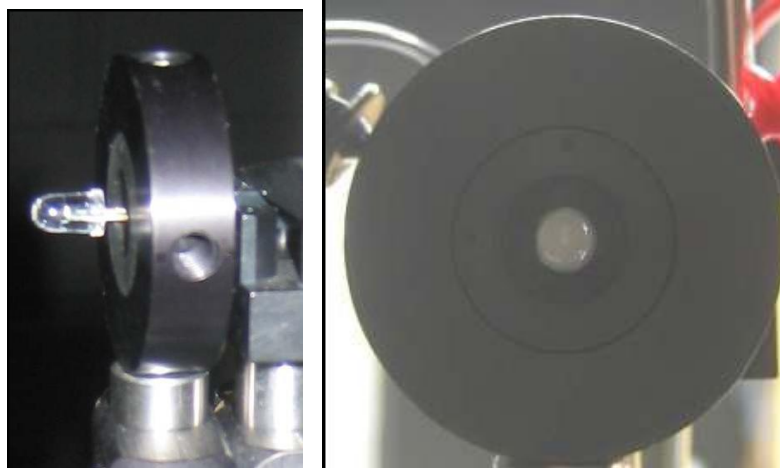


Fig. 4-5. LED holder used in the measurement of the emitted color of LEDs in MIKES.

4.2.3. Traceability

The spectral irradiance responsivity of the spectroradiometer is traceable to the national standard of spectral irradiance [Calibration certificate T-R 506]. The calibrations of the current-to-voltage converter Vinculum SP042 and digital voltmeter HP 3458A are traceable to the national standards of electricity [Calibration certificates INT-033, INT-032].

4.2.4. Measurement uncertainty

Uncertainty components for the emitted color and junction voltage of the LEDs have been presented in Tables below. The sensitivity coefficients of the uncertainty components have been calculated as the ratio between the relative standard uncertainty of the component and the standard deviation of the probability distribution of the component. The uncertainty components due to wavelength error and irradiance responsivity of the spectroradiometer have been estimated with Monte Carlo simulations.

Table 4-7. MIKES uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	normal	1	0.0010 0.0005	7	X
LED alignment, tilting		B	rectangular	$(<0.0001 - 0.0047)^\circ$ $(<0.0001 -$	<0.0001 <0.0001	∞	X

				0.0069)/°			
LED alignment, centering		B	rectangular	<0.0001/ mm	<0.0001 <0.0001	∞	X
Current feeding		B	rectangular	0.02/mA	<0.0001 <0.0001	∞	O
Calibration of spectroradiometer		B	normal	1	0.0001 0.0001	∞	O
Noise		B	rectangular	1	0.0001 0.0001	∞	X
Wavelength error		B	normal	(0.001 – 0.003)/nm	0.0002 0.0002	∞	O
Temperature correction of PMT		B	rectangular	1	<0.0001 <0.0001	∞	O
Measurement geometry		B	rectangular	1	<0.0001 <0.0001	∞	X
Combined standard uncertainty	--	--	normal	--	0.0011 0.0005	8 10	--

Table 4-8. MIKES uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	normal	1	0.0016 0.0007	7	X
LED alignment, tilting		B	rectangular	(<0.0001 – 0.0047)/° (<0.0001 – 0.0069)/°	<0.0001 <0.0001	∞	X
LED alignment, centering		B	rectangular	<0.0001/ mm	<0.0001 <0.0001	∞	X
Current feeding		B	rectangular	0.02/mA	<0.0001 <0.0001	∞	O
Calibration of spectroradiometer		B	normal	1	0.0001 0.0001	∞	O
Noise		B	rectangular	1	0.0002 0.0001	∞	X
Wavelength error		B	normal	(0.001 – 0.003)/nm	0.0007 0.0002	∞	O
Temperature correction of PMT		B	rectangular	1	<0.0001 <0.0001	∞	O
Measurement geometry		B	rectangular	1	<0.0001 <0.0001	∞	X
Combined standard uncertainty	--	--	normal	--	0.0017 0.0008	10 9	--

Table 4-9. MIKES uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	normal	1	0.0006 0.0009	7	X
LED alignment, tilting		B	rectangular	$(<0.0001 - 0.0047)^\circ$ $(<0.0001 - 0.0069)^\circ$	<0.0001 <0.0001	∞	X
LED alignment, centering		B	rectangular	$<0.0001/\text{mm}$	<0.0001 <0.0001	∞	X
Current feeding		B	rectangular	0.02/mA	<0.0001 <0.0001	∞	O
Calibration of spectroradiometer		B	normal	1	0.0001 0.0001	∞	O
Noise		B	rectangular	1	0.0002 0.0001	∞	X
Wavelength error		B	normal	$(0.001 - 0.003)/\text{nm}$	0.0002 0.0005	∞	O
Temperature correction of PMT		B	rectangular	1	<0.0001 <0.0001	∞	O
Measurement geometry		B	rectangular	1	<0.0001 <0.0001	∞	X
Combined standard uncertainty	--	--	normal	--	0.0006 0.0010	11 13	--

Table 4-10. MIKES uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	normal	1	0.0003 0.0008	7	X
LED alignment, tilting		B	rectangular	$(<0.0001 - 0.0047)^\circ$ $(<0.0001 - 0.0069)^\circ$	0.0053 0.0081	∞	X
LED alignment, centering		B	rectangular	$<0.0001/\text{mm}$	<0.0001 <0.0001	∞	X
Current feeding		B	rectangular	0.02/mA	<0.0001 <0.0001	∞	O
Calibration of spectroradiometer		B	normal	1	0.0001 0.0001	∞	O

Noise		B	rectangular	1	0.0005 0.0001	∞	X
Wavelength error		B	normal	$(0.001 - 0.003)/\text{nm}$	0.0002 0.0001	∞	O
Temperature correction of PMT		B	rectangular	1	<0.0001 <0.0001	∞	O
Measurement geometry		B	rectangular	1	0.0002 0.0003	∞	X
Combined standard uncertainty	--	--	normal	--	0.0054 0.0081	∞ ∞	--

Table 4-11. MIKES uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	normal	1	0.0012 0.0011	7	X
LED alignment, tilting		B	rectangular	$(<0.0001 - 0.0047)^\circ$ $(<0.0001 - 0.0069)^\circ$	0.0002 0.0003	∞	X
LED alignment, centering		B	rectangular	<0.0001/mm	<0.0001 <0.0001	∞	X
Current feeding		B	rectangular	0.02/mA	<0.0001 <0.0001	∞	O
Calibration of spectroradiometer		B	normal	1	0.0001 0.0001	∞	O
Noise		B	rectangular	1	0.0063 0.0068	∞	X
Wavelength error		B	normal	$(0.001 - 0.003)/\text{nm}$	0.0006 0.0003	∞	O
Temperature correction of PMT		B	rectangular	1	<0.0001 <0.0001	∞	O
Measurement geometry		B	rectangular	1	<0.0001 <0.0001	∞	X
Combined standard uncertainty	--	--	normal	--	0.0065 0.0069	∞ ∞	--

Table 4-12. MIKES uncertainty budget of junction voltage measurement for red LEDs (R).

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (mV)	Deg. of freedom	Correlated?
Calibration of voltmeter		B	normal	1	0.02	∞	O

Junction position dependence		B	rectangular	1	0.03	∞	X
Stability of junction voltage		B	rectangular	1	0.30	∞	X
Combined standard uncertainty (mV)	--	--	normal	--	0.30	∞	--

Table 4-13. MIKES uncertainty budget of junction voltage measurement for green LEDs (G).

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (mV)	Deg. of freedom	Correlated?
Calibration of voltmeter		B	normal	1	0.03	∞	O
Junction position dependence		B	rectangular	1	0.12	∞	X
Stability of junction voltage		B	rectangular	1	0.44	∞	X
Combined standard uncertainty (mV)	--	--	normal	--	0.46	∞	--

Table 4-14. MIKES uncertainty budget of junction voltage measurement for blue LEDs (B).

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (mV)	Deg. of freedom	Correlated?
Calibration of voltmeter		B	normal	1	0.03	∞	O
Junction position dependence		B	rectangular	1	0.10	∞	X
Stability of junction voltage		B	rectangular	1	0.41	∞	X
Combined standard uncertainty (mV)	--	--	normal	--	0.42	∞	--

Table 4-15. MIKES uncertainty budget of junction voltage measurement for white LEDs (W).

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (mV)	Deg. of freedom	Correlated?
Calibration of voltmeter		B	normal	1	0.03	∞	O
Junction position dependence		B	rectangular	1	0.20	∞	X
Stability of junction voltage		B	rectangular	1	0.45	∞	X

Combined standard uncertainty (mV)	--	--	normal	--	0.50	∞	--
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Table 4-16. MIKES uncertainty budget of junction voltage measurement for diffuser-type green LEDs (D).

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (mV)	Deg. of freedom	Correlated?
Calibration of voltmeter		B	normal	1	0.03	∞	O
Junction position dependence		B	rectangular	1	0.07	∞	X
Stability of junction voltage		B	rectangular	1	0.30	∞	X
Combined standard uncertainty (mV)	--	--	normal	--	0.31	∞	--

4.3. CMS-ITRI

4.3.1. Measurement setup

This system use scanning type spectroradiometer to catch the spectrum of light source from detector. By comparing the signal of standard lamp and LED, to calculate the relative LED spectrum. The wavelength range which from 250 nm to 700 nm using GAMMA spectroradiometer, and wavelength range from 350 nm to 1100 nm using ARC spectroradiometer. Therefore in this comparison the Red colour LED using ARC spectroradiometer, others using GAMMA spectroradiometer to get the spectrum. The back of this system have laser for alignment and have a light trap to trap the backward light when measuring. There have alignment CCD and a display for aligning lamp. Using the DC multiple standard resistor, two voltage meter and DC power supply that give the LED current and monitor the current and voltage of the junction of LED. Then the emitted colour of LED was calculated from relative spectrum according to CIE 1931-XYZ transformation.

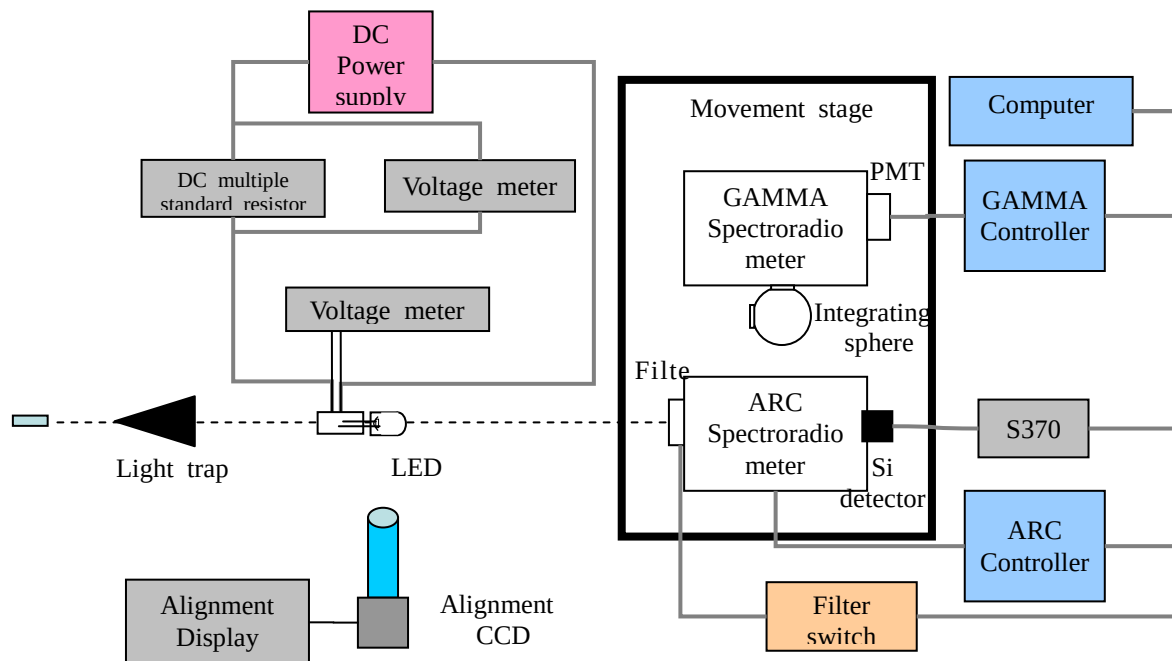


Fig. 4-6. Emitted colour of LED measurement system in CMS-ITRI.

4.3.2. Mounting and alignment

The LED is mounting by a holder that has two pins connect and has two wires at the end of holder for power current connecting. The holder is located at the top of the multiple stages that have rotating and movement stages for alignment. By using alignment CCD to check the mechanical axis of LED align to the axis of setting optical axis that is using the laser for setting previously.

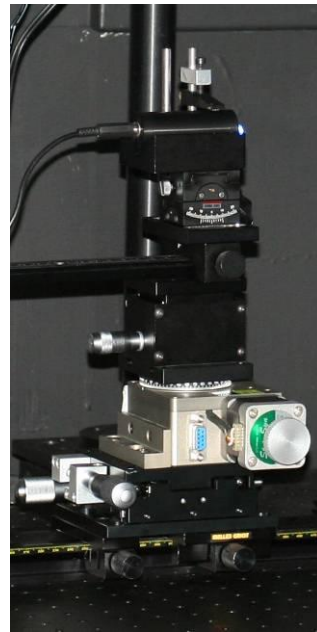
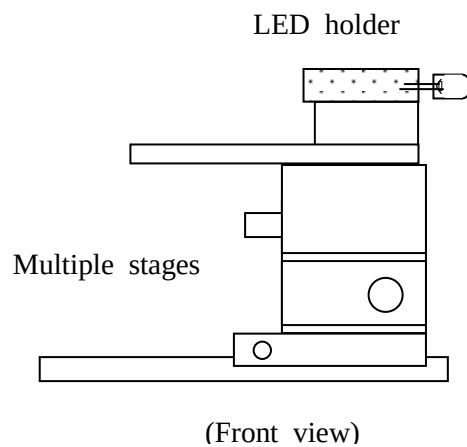


Fig. 4-7. LED Mounting and alignment system in CMS-ITRI.

4.3.3. Traceability

The traceability of Emitted colour of LED is trace to the spectral irradiance standard lamp by spectroradiometric system. Then the spectral irradiance standard lamp trace to NMIA.

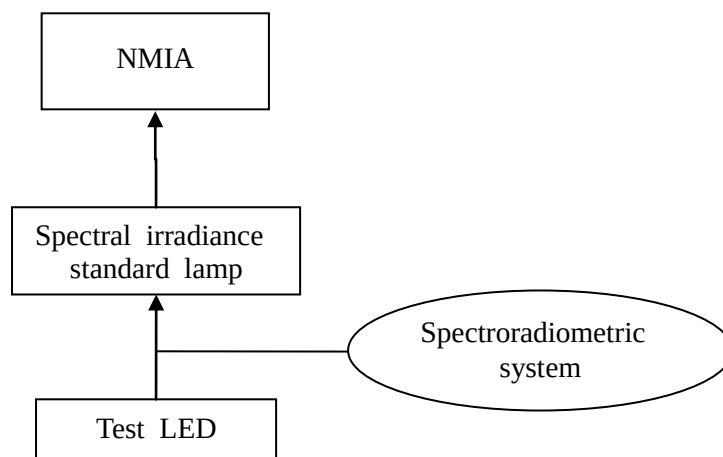


Fig. 4-8. Traceability of measurement system in CMS-ITRI.

4.3.4. Measurement uncertainty

Uncertainty budget of averaged LED intensity measurement:

1. Repeatability of test LED:

The repeatability of test LED is record the optical current by using current meter several times a day and measure several days. Calculate the standard deviation of all the data.

2. LED mechanical axis alignment:

The LED mechanical axis must coaxial of system optical axis. Consider the maximum deviation of misalignment by rotating the LED at horizontal plane and distance deviation that affect the deviation of the colour coordinate.

3. Wavelength shift:

Because using scanning type spectroradiometer which rotate the grating to catch the signal. Therefore consider the rotating mechanism error that causing the wavelength shift then affect the colour coordinate. Thus consider the maximum deviation of LED wavelength shift and calculate the deviation of colour coordinate.

4. Chromaticity coordinate traceability of standard lamp:

By calculating the uncertainty that relation of spectrum standard deviation of standard lamp and LED, and suppose the different spectrum is independent. Then using CIE 1931-XYZ transformations to calculate the uncertainty of chromaticity coordinate traceability of standard lamp.

Table 4-17. CMS-ITRI uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	t	1	0.0015 0.0006	6	X
LED mechanical axis alignment		B	rectangular	1	0.0014 0.0022	200	O
Wavelength shift		B	rectangular	1	0.0001 0.0001	200	X
Chromaticity coordinate traceability of standard lamp		B	rectangular	1	0.0001 0.0001	5000	X
Combined standard uncertainty	--	--	normal	--	0.0014 0.0023	207 201	--

Table 4-18. CMS-ITRI uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	t	1	0.0022 0.0024	6	X
LED mechanical axis alignment		B	rectangular	1	0.0014 0.0022	200	O
Wavelength shift		B	rectangular	1	0.0004 0.0001	200	X
Chromaticity coordinate traceability of standard lamp		B	rectangular	1	0.0006 0.0005	5000	X
Combined standard uncertainty	--	--	normal	--	0.0026 0.0033	13 21	--

Table 4-19. CMS-ITRI uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	t	1	0.0013 0.0001	6	X
LED mechanical axis alignment		B	rectangular	1	0.0014 0.0022	200	O
Wavelength shift		B	rectangular	1	0.0002 0.0005	200	X
Chromaticity coordinate traceability of standard lamp		B	rectangular	1	0.0002 0.0005	5000	X
Combined standard uncertainty	--	--	normal	--	0.0019 0.0025	29 145	--

Table 4-20. CMS-ITRI uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	t	1	0.0031 0.0015	6	X
LED mechanical axis alignment		B	rectangular	1	0.0014 0.0022	200	O
Wavelength shift		B	rectangular	1	0.0002 0.0002	200	X

Chromaticity coordinate traceability of standard lamp		B	rectangular	1	0.0009 0.0009	5000	X
Combined standard uncertainty	--	--	normal	--	0.0034 0.0028	10 62	--

Table 4-21. CMS-ITRI uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Repeatability		A	t	1	0.0047 0.0051	6	X
LED mechanical axis alignment		B	rectangular	1	0.0014 0.0022	200	O
Wavelength shift		B	rectangular	1	0.0004 0.0002	200	X
Chromaticity coordinate traceability of standard lamp		B	rectangular	1	0.0096 0.0084	5000	X
Combined standard uncertainty	--	--	normal	--	0.011 0.010	165 92	--

Uncertainty budget of junction voltage measurement

1. Repeatability of test LED:

The repeatability of test LED is record the junction voltage by using voltage meter several times a day and measure several days when measuring the LED averaged intensity. Calculate the standard deviation of all the data.

2. Resolution of voltmeter:

To consider the drift when measure the junction voltage that is the maximum digit of voltage meter.

3. Long-term drift of voltmeter:

Long-term drift of voltmeter is the drift of the traceability since the past. Calculate the maximum deviation of the uncertainty drift.

4. Voltmeter calibration:

The uncertainty of voltmeter is drive from the relative expand uncertainty calibrated by National measurement laboratory (NML) in Taiwan.

Table 4-22. CMS-ITRI uncertainty budget of junction voltage measurement for red LEDs (R).

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Repeatability	0.030	A	t	1	0.030	200	X
Resolution of voltmeter	0.003	B	rectangular	1	0.003	200	O
Long-term drift of voltmeter	0.026	B	rectangular	1	0.026	200	O
Voltmeter calibration	0.001	B	normal	1	0.001	5000	O
Combined standard uncertainty (%)	--	--	normal	--	0.04	395	--

Table 4-23. CMS-ITRI uncertainty budget of junction voltage measurement for green LEDs (G).

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Repeatability	0.110	A	t	1	0.110	200	X
Resolution of voltmeter	0.003	B	rectangular	1	0.003	200	O
Long-term drift of voltmeter	0.026	B	rectangular	1	0.026	200	O
Voltmeter calibration	0.001	B	normal	1	0.001	5000	O
Combined standard uncertainty (%)	--	--	normal	--	0.11	222	--

Table 4-24. CMS-ITRI uncertainty budget of junction voltage measurement for blue LEDs (B).

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Repeatability	0.030	A	t	1	0.030	200	X
Resolution of voltmeter	0.003	B	rectangular	1	0.003	200	O
Long-term drift of voltmeter	0.026	B	rectangular	1	0.026	200	O
Voltmeter calibration	0.001	B	normal	1	0.001	5000	O

Combined standard uncertainty (%)	--	--	normal	--	0.04	378	--
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Table 4-25. CMS-ITRI uncertainty budget of junction voltage measurement for white LEDs (W).

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Repeatability	0.060	A	t	1	0.060	200	X
Resolution of voltmeter	0.003	B	rectangular	1	0.003	200	O
Long-term drift of voltmeter	0.026	B	rectangular	1	0.026	200	O
Voltmeter calibration	0.001	B	normal	1	0.001	5000	O
Combined standard uncertainty (%)	--	--	normal	--	0.07	274	--

Table 4-26. CMS-ITRI uncertainty budget of junction voltage measurement for diffuser-type green LEDs (D).

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Repeatability	0.070	A	t	1	0.070	200	X
Resolution of voltmeter	0.003	B	rectangular	1	0.003	200	O
Long-term drift of voltmeter	0.026	B	rectangular	1	0.026	200	O
Voltmeter calibration	0.001	B	normal	1	0.001	5000	O
Combined standard uncertainty (%)	--	--	normal	--	0.08	252	--

4.4. PTB

4.4.1. Measurement setup

오류! 참조 원본을 찾을 수 없습니다. below shows the measurement setup in principle. To enable the measurement of all the desired quantities, a special mechanism is needed. This allows the following functionality: the alignment of the LED transfer standard to the

optical axis of the system, the rotation of the LED transfer standard around its horizontal axis φ and rotation around its vertical axis θ . Furthermore, it allows the variation of the distance r between the selected detector and the LED transfer standard. Opposite the LED transfer standard, a rotating wheel is used for a quick detector selection. Additionally, there is a laser and a CCD camera mounted to enable the easy alignment of the LED transfer standard. Due to the rotation of φ angle, the interconnection between the power supply and the LED under test prohibits an endless rotation.

Thus, in the case of luminous flux measurements after a little more than one rotation, a stop is needed. The next movement will then be the turn back and so on.

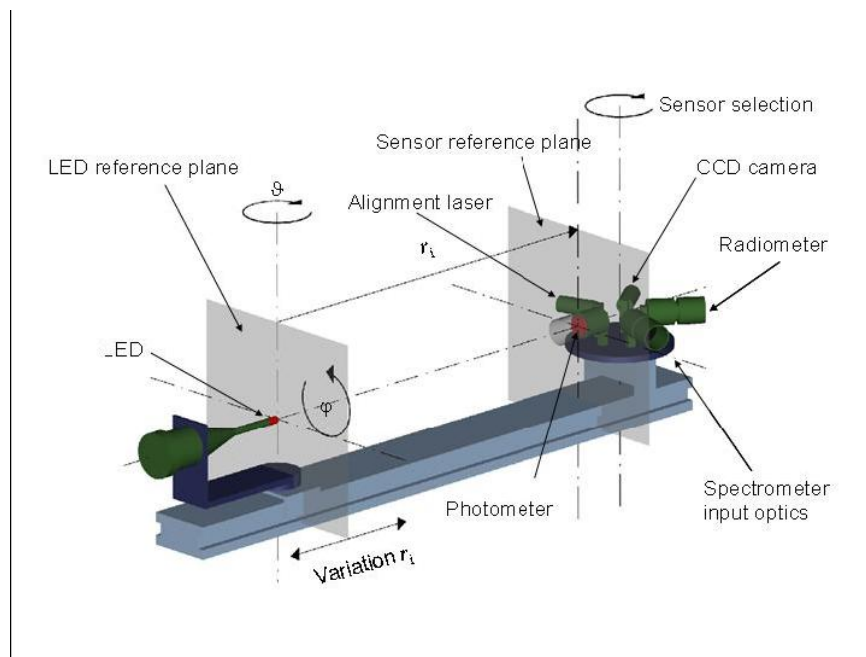


Fig. 4-9. Measurement setup for averaged LED intensity in PTB.

4.4.2. Mounting and alignment

오류! 참조 원본을 찾을 수 없습니다. below shows the holder which was used to hold, align and operate each LED. A high reflecting cone directly behind the installed LED allows for the indirect measurement of the backward directed partial luminous flux of the LEDs, which also contributes to the total luminous flux.

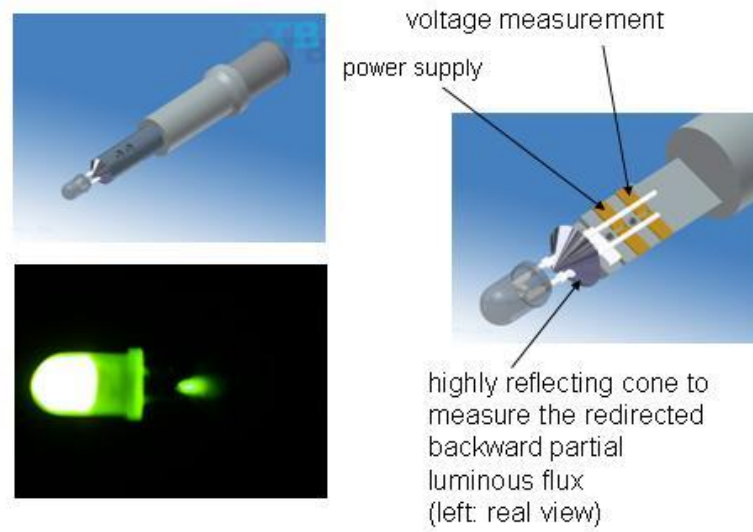


Fig. 4-10. Pictures of the LED holder used in the measurement of the averaged LED intensity in PTB.

4.4.3. Traceability

The primary standards for the measured quantities are traceable to national standards.

4.4.4. Measurement uncertainty

For determination of the chromaticity coordinates (x, y) and their standard measurement uncertainty $U(x)$ and $U(y)$, a Monte Carlo Simulation was used. This simulation based on measuring results from an array spectroradiometer which was used.

The next statement shows the formula to correct the chromaticity coordinates from the MC simulation for nominal operating values of a blue LED. There was no correction for LED current, because that influence is negligible.

$$x_0 = \left(\frac{\frac{T_0 v_M}{E_{cp}[k] + v_0} + 273}{T_0 + 273} \right)^{-\alpha x} x + \Delta x_{bp} + \Delta x_{set}$$

$$y_0 = \left(\frac{\frac{T_0 v_M}{E_{cp}[k] + v_0} + 273}{T_0 + 273} \right)^{-\alpha y} y + \Delta y_{bp} + \Delta y_{set}$$

	"DESCRIPTION"	"UNIT"	"SYMBOL"	"VALUE"	"UNCERTAINTY (IN)"	"PD"	"DOF"
data =	"LED Nominal Ambient Temperature"	"°C"	T ₀	25	0	"norm"	∞
	"LED Nominal Voltage"	"V"	v ₀	Valv0	ValUv0	"norm"	9
	"Exponent LED Voltage/Temperature Corr."	"1"	k	Valk	ValUk	"norm"	9
	"Exponent Chromaticity Coordinate x corr"	"1"	m _x	-0.11310	0.01351	"norm"	5
	"Chromaticity Coordinate x from MC Sim."	"1"	x	0.12330	0.0001935	"norm"	50
	"Band pass correction spectrometer in x"	"1"	Δx _{bp}	0	0.0001	"norm"	50
	"Stray light correction spectrometer in x"	"1"	Δx _{sest}	0	0.0003	"norm"	50
	"LED Voltage Reading"	"V"	v _H	3.4410	0.0005 × 3.4410	"norm"	10
	"DESCRIPTION"	"UNIT"	"SYMBOL"	"VALUE"	"UNCERTAINTY (IN)"	"PD"	"DOF"
data =	"LED Nominal Ambient Temperature"	"°C"	T ₀	25	0	"norm"	∞
	"LED Nominal Voltage"	"V"	v ₀	Valv0	ValUv0	"norm"	9
	"Exponent LED Voltage/Temperature Corr."	"1"	k	Valk	ValUk	"norm"	9
	"Exponent Chromaticity Coordinate x corr"	"1"	m _y	0.44512	0.049821	"norm"	5
	"Chromaticity Coordinate x from MC Sim."	"1"	y	0.08404	0.0004920	"norm"	50
	"Band pass correction spectrometer in y"	"1"	Δy _{bp}	0	0.0004	"norm"	50
	"Stray light correction spectrometer in y"	"1"	Δy _{sest}	0	0.0002	"norm"	50
	"LED Voltage Reading"	"V"	v _H	3.4410	0.0005 × 3.4410	"norm"	10

**Table 4-27. PTB uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R).
Upper values for x, lower values for y.**

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
LED nominal ambient temperature	0 K			-2.3E-6 2.28E-6	0		
LED nominal voltage for 25 °C	0.00073 V	A	normal	0.00166 -0.00164	1.21E-6 1.2E-6	9	
LED voltage reading	0.00060 V	A	normal	-0.00166 0.00164	-9.9E-7 9.8E-7	10	
Exponent chromaticity coordinate correction	0.00042 0.0016	B	normal	-0.0012 -5.136E-4	-5.0E-7 -8.4E-7	5	
Exponent LED voltage/temperature correction	0.0067	B	normal	0.0031 -0.0031	2.1E-5 -2.1E-5	9	
Bandpass correction of spectrometer	0.00040 0.00040	B	normal	1	0.00040 0.00040	50	
Chromaticity coordinate from MC simulation	0.00017 0.00016	A	normal	1.00021	1.7E-4 1.6E-4	50	
Straylight correction of spectrometer	0.00040 0.00010	B	normal	1	0.00040 0.00010	50	
Combined standard uncertainty	--	--	normal	--	0.00059 0.00044	116 72	--

Table 4-28. PTB uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
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LED nominal ambient temperature	0 K		normal	-4.29E-6 -2.26E-6	0	∞	
LED nominal voltage for 25 °C	0.0026 V	A	normal	0.00094 0.000495	2.4E-6 1.3 E-6	9	
LED voltage reading	0.0011 V	A	normal	-0.00094 -0.000496	-1.1E-6 -5.6E-7	10	
Exponent chromaticity coordinate correction	0.014 0.00086	B	normal	-0.00047 -0.00224	-6.6E-6 -1.9E-6	5	
Exponent LED voltage/temperature correction	0.013	B	normal	0.00331 0.00174	4.2E-5 2.2E-5	9	
Bandpass correction of spectrometer	0.00080 0.0016	B	normal	1	0.00080 0.0016	50	
Chromaticity coordinate from MC simulation	0.00051 0.00047	A	normal	0.999915	0.00050 0.00047	50	
Straylight correction of spectrometer	0.00030 0.00012	B	normal	1	0.00030 0.00012	50	
Combined standard uncertainty	--	--	normal	--	0.00099 0.0017	100 59	--

Table 4-29. PTB uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
LED nominal ambient temperature	0 K		normal	1.195E-6 -3.20E-6	0	∞	
LED nominal voltage for 25 °C	0.0017 V	A	normal	-0.00035 0.000933	-5.9E-7 1.6E-6	9	
LED voltage reading	0.00080 V	A	normal	0.000349 -0.000934	2.8E-7 -7.5E-7	10	
Exponent chromaticity coordinate correction	0.014 0.050	B	normal	-0.000289 -0.000197	-3.9E-6 -9.8E-6	5	
Exponent LED voltage/temperature correction	0.0077	B	normal	-0.0012 0.0032	-9.2E-6 2.5E-5	9	
Bandpass correction of spectrometer	0.00010 0.00040	B	normal	1	0.00010 0.00040	50	
Chromaticity coordinate from MC simulation	0.00019 0.00049	A	normal	1	0.00019 0.00049	50	
Straylight correction of spectrometer	0.00030 0.00020	B	normal	1	0.00030 0.00020	50	
Combined standard uncertainty	--	--	normal	--	0.00037 0.00067	98 114	--

Table 4-30. PTB uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
LED nominal ambient temperature	0 K		normal	8.155E-6 6.366E-6	0	∞	
LED nominal voltage for 25 °C	0.0025 V	A	normal	-0.00163 -0.00127	-4.1E-6 -3.2E-6	9	
LED voltage reading	0.0011 V	A	normal	0.00163 0.00128	1.8E-6 1.4E-6	10	
Exponent chromaticity coordinate correction	0.017 0.014	B	normal	-0.00113 -0.00113	-2.0E-5 -1.5E-5	5	
Exponent LED voltage/temperature correction	0.012	B	normal	-0.00563 -0.0044	-6.9E-5 -5.4E-5	9	
Bandpass correction of spectrometer	0.00010 0.00030	B	normal	1	0.00010 0.00030	50	
Chromaticity coordinate from MC simulation	0.00083 0.0010	A	normal	1.00068 1.00053	8.3E-4 0.0010	50	
Straylight correction of spectrometer	0.00010 0.00010	B	normal	1	0.00010 0.00010	50	
Combined standard uncertainty	--	--	normal	--	0.00084 0.00105	53 60	--

Table 4-31. PTB uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
LED nominal ambient temperature	0 K		normal	-3.83E-6 -1.77E-6	0	∞	
LED nominal voltage for 25 °C	0.0017 V	A	normal	0.00112 0.00052	1.93E-6 8.94E-7	9	
LED voltage reading	0.00080 V	A	normal	-0.00112 -0.00052	-8.9E-7 -4.1E-7	10	
Exponent chromaticity coordinate correction	0.014 0.00086	B	normal	-0.000423 -0.001753	-5.9E-6 -1.5E-6	5	
Exponent LED voltage/temperature correction	0.0080	B	normal	0.00372 0.00172	3.0E-5 1.4E-5	9	
Bandpass correction of spectrometer	0.00070 0.0014	B	normal	1	0.00070 0.0014	50	
Chromaticity coordinate from MC simulation	0.00050 0.00042	A	normal	0.999402 0.999933	5.0E-4 0.00042	50	
Straylight correction of spectrometer	0.00020 0.00010	B	normal	1	0.00020 0.00010	50	

Combined standard uncertainty	--	--	normal	--	0.00088 0.0015	100 59	--
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Table 4-32. PTB uncertainty budget of junction voltage measurement of blue LED (example).

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (mV)	Deg. of freedom	Correlated?
Calibration of voltmeter	0.000050	B	rectangular	3.44	0.17	10	
Junction position dependence	0.00052 V	B	rectangular	-1	-0.52	10	
Reproducibility	0.00058 V	A	normal	1	0.58	10	
Combined standard uncertainty (mV)	--	--	normal	--	0.80	35	--

4.5. NMIJ

4.5.1. Measurement setup

The facility is composed of a spectroradiometer, an incidence-optical system (4' integrating sphere), a LED gonio-stage and a laser-alignment system. The spectroradiometer is using single monochromator with a focal length of 50 cm.

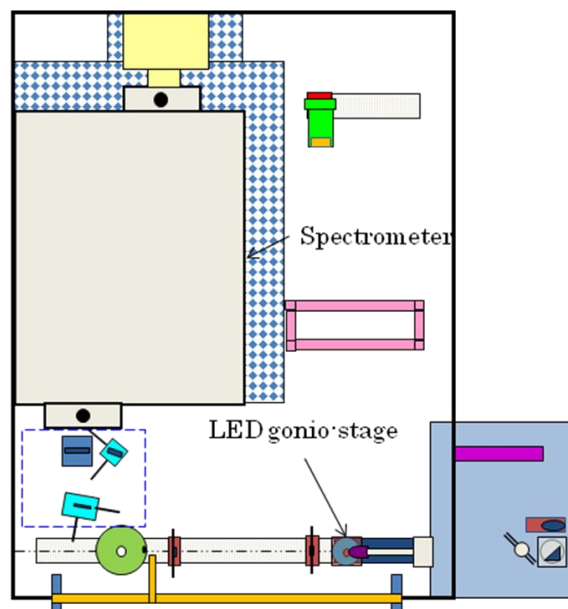


Fig. 4-11. Calibration facility for LED colour in NMIJ.

4.5.2. Mounting and alignment

- a) The laser system is used for LED alignment.
 b) LED holder is mounted to the gonio-stage.
 c) 오류! 참조 원본을 찾을 수 없습니다. shows picture of the LED holder. (Pin socket is used to mount LED)



Fig. 4-12. LED mount socket in NMIJ.

4.5.3. Traceability

Relative spectral distribution of the test LED $\Rightarrow$ spectral irradiance standard at NMIJ.

4.5.4. Measurement uncertainty

Table 4-33. NMIJ uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R).
 Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Spectral irradiance calibration (including repeatability)		A + B	gaussian	--	0.00011 0.00011	∞	X
Wavelength uncertainty of LED spectral distribution	Random 0.1 nm, systematic (correlation factor) 0.1 nm	A + B	gaussian (random factor), rectangular (systematic factor)	--	0.00016 0.00005	∞	X
Effect of slit function width		B	rectangular	1	0.00015 0.00015	∞	X
Alignment of LED	Centering 1 mm, angular 1°	B	rectangular	0.0001 0.0001	0.00009 0.00007	∞	X
Effect of stray light		B	rectangular	1	0.00022 0.00017	∞	O
Repeatability of LED (including noise and drift)		A	t	1	0.00008 0.00010	4	X

Combined standard uncertainty	--	--	normal	--	0.0004 0.0003	∞ ∞	--
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Table 4-34. NMIJ uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Spectral irradiance calibration (including repeatability)	Uncertainty of NMIJ irradiance scale	A + B	gaussian	--	0.00054 0.00057	∞	X
Wavelength uncertainty of LED spectral distribution	Random 0.1 nm, systematic (correlation factor) 0.1 nm	A + B	gaussian (random factor), rectangular (systematic factor)	--	0.00040 0.00027	∞	X
Effect of slit function width		B	rectangular	1	0.00036 0.00071	∞	X
Alignment of LED	Centering 1 mm, angular 1°	B	rectangular	0.0002 0.0001	0.00015 0.00012	∞	X
Effect of stray light		B	rectangular	1	0.00043 0.00082	∞	O
Repeatability of LED (including noise and drift)		A	t	1	0.00008 0.00009	4	X
Combined standard uncertainty	--	--	normal	--	0.0009 0.0013	∞ ∞	--

Table 4-35. NMIJ uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Spectral irradiance calibration (including repeatability)	Uncertainty of NMIJ irradiance scale	A + B	gaussian	--	0.00012 0.00036	∞	X
Wavelength uncertainty of LED spectral distribution	Random 0.1 nm, systematic (correlation factor) 0.1 nm	A + B	gaussian (random factor), rectangular (systematic factor)	--	0.00015 0.00043	∞	X
Effect of slit function width		B	rectangular	1	0.00010 0.00016	∞	X

Alignment of LED	Centering 1 mm, angular 1°	B	rectangular	< 0.0001 0.0001	0.00003 0.00007	∞	X
Effect of stray light		B	rectangular	1	0.00024 0.00043	∞	O
Repeatability of LED (including noise and drift)		A	t	1	0.00010 0.00010	4	X
Combined standard uncertainty	--	--	normal	--	0.0003 0.0007	∞ ∞	--

Table 4-36. NMIJ uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Spectral irradiance calibration (including repeatability)	Uncertainty of NMIJ irradiance scale	A + B	gaussian	--	0.00060 0.00079	∞	X
Wavelength uncertainty of LED spectral distribution	Random 0.1 nm, systematic (correlation factor) 0.1 nm	A + B	gaussian (random factor), rectangular (systematic factor)	--	0.00019 0.00027	∞	X
Effect of slit function width		B	rectangular	1	0.00010 0.00010	∞	X
Alignment of LED	Centering 1 mm, angular 1°	B	rectangular	0.0002 0.0001	0.00016 0.00011	∞	X
Effect of stray light		B	rectangular	1	< 0.0001 < 0.0001	∞	O
Repeatability of LED (including noise and drift)		A	t	1	0.00011 0.00012	4	X
Combined standard uncertainty	--	--	normal	--	0.0007 0.0009	∞ ∞	--

Table 4-37. NMIJ uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Spectral irradiance calibration (including repeatability)	Uncertainty of NMIJ irradiance scale	A + B	gaussian	--	0.00060 0.00059	∞	X

Wavelength uncertainty of LED spectral distribution	Random 0.1 nm, systematic (correlation factor) 0.1 nm	A + B	gaussian (random factor), rectangular (systematic factor)	--	0.00020 0.00017	∞	X
Effect of slit function width		B	rectangular	1	0.00033 0.00064	∞	X
Alignment of LED	Centering 1 mm, angular 1°	B	rectangular	0.0001 0.0001	0.00014 0.00012	∞	X
Effect of stray light		B	rectangular	1	0.00017 0.00040	∞	O
Repeatability of LED (including noise and drift)		A	t	1	0.00020 0.00072	4	X
Combined standard uncertainty	--	--	normal	--	0.0008 0.0012	∞ ∞	--

Table 4-38. NMIJ uncertainty budget of junction voltage measurement.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (V)	Deg. of freedom	Correlated?
Calibration of DMM		B	gaussian	1	0.0001	∞	O
Repeatability (including effect of temperature difference)		A	gaussian	1	0.0001 ~ 0.0009	4	X
Junction position		B	rectangular	1	0.0003	∞	X
Combined standard uncertainty (V)	--	--	normal	--	0.0003 ~ 0.0010	6	--

4.6. CENAM

4.6.1. Measurement setup

As established in the comparison Protocol⁷, the Averaged LED Intensity measurements were performed by using the measurement array setup in order to reproduce the CIE Standard Condition B⁸, see Fig. 4-13.

⁷ D. H. Lee, *Technical Protocol on APMP Supplementary Comparison of LED Measurements*, KRISS, Korea, (2008).

⁸ Commission International de l'Eclairage, *Measurement of LEDs*, Publication CIE N° 127, Genève, (2007).

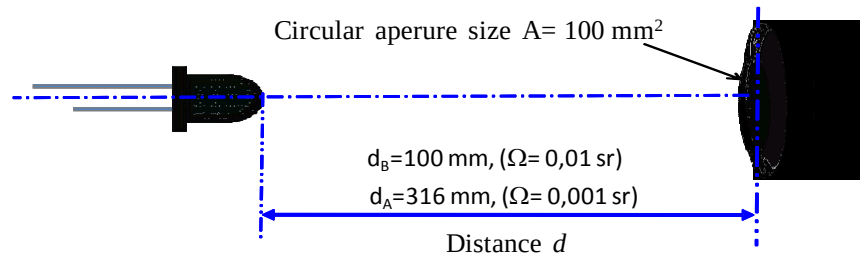


Fig. 4-13. CIE Standard Condition B established for Averaged LED Intensity in CENAM.

Since the key condition to be kept in order to reproduce the CIE Standard Condition B is the established solid angle of $\Omega = 0.01 \text{ sr}$; then for a given aperture size A , the corresponding distance d can be deduced from Eq. (4.1):

$$d = \sqrt{\frac{A}{\Omega}} \quad (4.1)$$

오류! 참조 원본을 찾을 수 없습니다. shows the aperture area and distance used at CENAM in order to reproduce the sought solid angle.

Table 4-39. Parameters used at CENAM to reproduce the CIE Standard Condition B.

Aperture diameter, (mm)	Aperture area, $A \text{ (mm}^2\text{)}$	Distance, $d \text{ (mm)}$
10.058	79.454	89

The selected aperture was coupled to the sensitive surface of a portable spectroradiometer, taking care of maintaining the corresponding distance, see Fig. 4-14.



Fig. 4-14. Coupling between the aperture and spectroradiometer in CENAM.

4.6.2. Mounting and alignment

As stated in the Comparison Protocol, the emitted color measurements required to consider the LED geometrical axis to lie along the measurement optical axis, see Fig. 4-15.

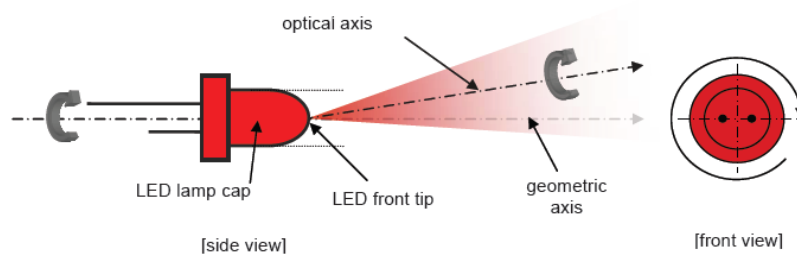


Fig. 4-15. LED emitted color geometry.

This alignment between axes required to assemble an LED mounting device having at least six degrees of freedom for the position adjustment: translational, height, transverse, centering angle, translational tilt angle, and transverse tilt angle. This special mounting device consisted of an LED holder, a high load jack, an X-Y translational stage, a rotation platform, and a pair of perpendicularly coupled goniometers, see Fig. 4-16.

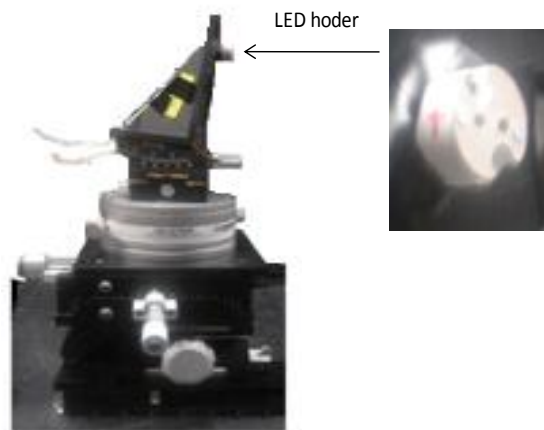


Fig. 4-16. LED mounting device in CENAM.

Thus in order to define the measurement system optical axis, the height of the LED holder was used as high reference, and propagated along the optical bench with the use of an alignment laser beam, and fixed by using an alignment jig, see Fig. 4-17.

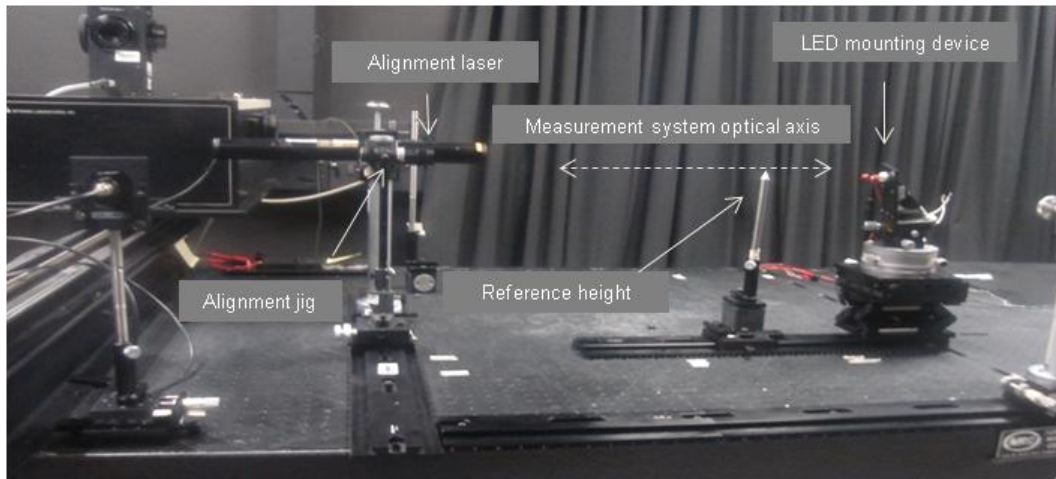


Fig. 4-17. Measurement system optical axis definition in CENAM.

Since the length of the several LEDs terminals was different for each device, it was necessary to define a reference plane in order to accurately reproduce the distance d given in 오류! 참조 원본을 찾을 수 없습니다. between the LED tip and the aperture plane; this was achieved by locating a flat plate aside of the LED holder, see Fig. 4-18.

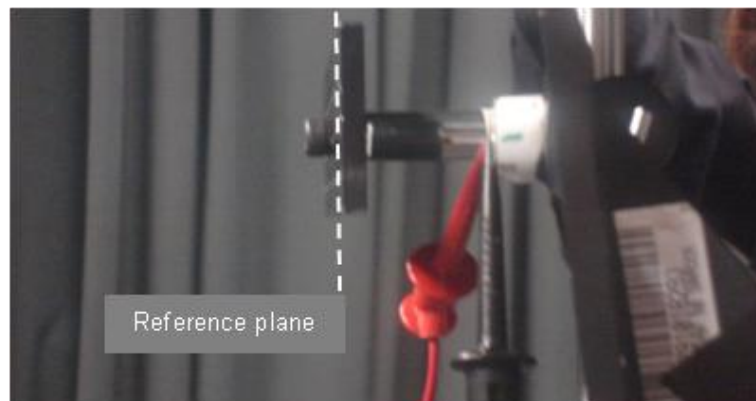


Fig. 4-18. Reference plane for distance stated in CIE Standard Condition B in CENAM.

With the measurement array aligned, the LEDs were placed in the holder, see Fig. 4-19, and aligned by using the reference plane defined by the flat plate and the alignment jig; as to obtain the view of the LED as established in the Comparison Protocol, see Fig. 4-20.



Fig. 4-19. LED insertion in the holder in CENAM.

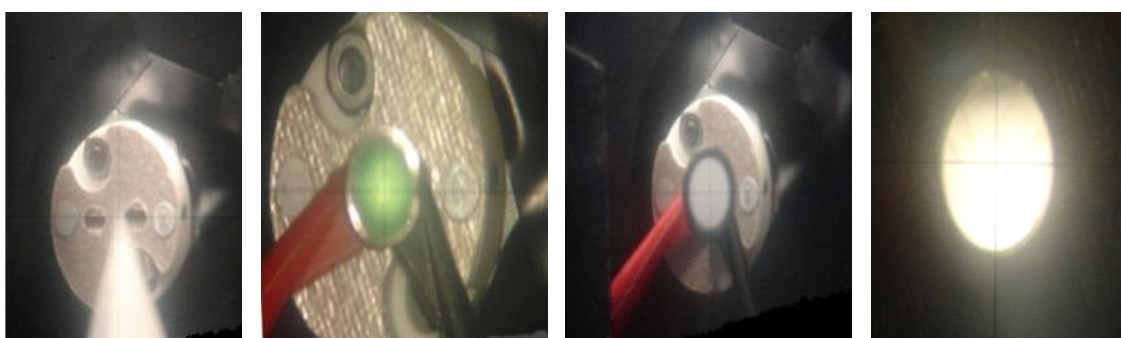


Fig. 4-20. Lamp-type and diffuser-type LEDs alignment views in CENAM.

4.6.3. Traceability

The emitted color related quantities were obtained from the LEDs spectral irradiance measurements by following the CIE guidelines⁹. The spectral irradiance measurements are traceable to the SI units through a set of FEL type lamps calibrated against the primary standards maintained at the NMIs of USA and France, see Fig. 4-21.

⁹ Commission International de l'Eclairage, *Method of Measuring and Specifying Color Rendering Properties Light Source*, Publication CIE N° 13.3, Genève, (1994).

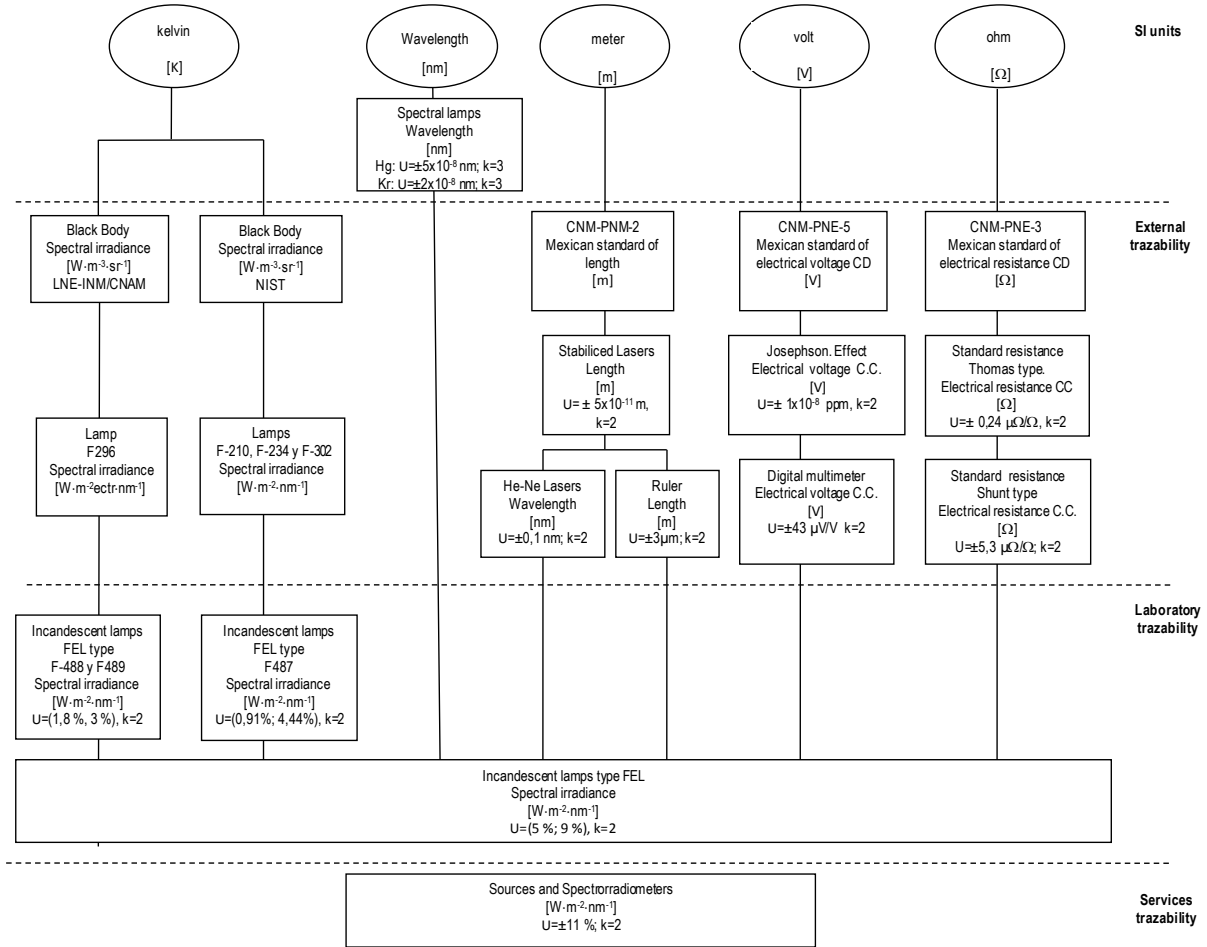


Fig. 4-21. Traceability chart for the spectral irradiance measurements performed at CENAM.

4.6.4. Measurement uncertainty

The color chromaticity coordinates were obtained from the tristimulus values, X, Y and Z, by using the CIE recommendation and Eq. (4.2):

$$x = \frac{X}{X+Y+Z} = \frac{\sum_{400}^{750} E(\lambda) \bar{x}(\lambda) \Delta\lambda}{\sum_{400}^{750} E(\lambda) \bar{x}(\lambda) \Delta\lambda + \sum_{400}^{750} E(\lambda) \bar{y}(\lambda) \Delta\lambda + \sum_{400}^{750} E(\lambda) \bar{z}(\lambda) \Delta\lambda}, \quad (4.2.a)$$

$$y = \frac{Y}{X+Y+Z} = \frac{\sum_{400}^{750} E(\lambda) \bar{y}(\lambda) \Delta\lambda}{\sum_{400}^{750} E(\lambda) \bar{x}(\lambda) \Delta\lambda + \sum_{400}^{750} E(\lambda) \bar{y}(\lambda) \Delta\lambda + \sum_{400}^{750} E(\lambda) \bar{z}(\lambda) \Delta\lambda}, \quad (4.2.b)$$

where $\bar{x}$, $\bar{y}$ and $\bar{z}$ are the CIE average spectral tristimulus values; $E(\lambda) = E_{\text{rel}560}(\lambda)$ is the relative spectral irradiance calculated for 560 nm; and $\Delta\lambda = 1$ nm is the wavelength step at which the involved data was processed.

From Eq. (4.2) it is possible to observe that the spectral irradiance is the unique input quantity to be considered in the uncertainty estimation for chromaticity

coordinates, see Fig. 4-22.

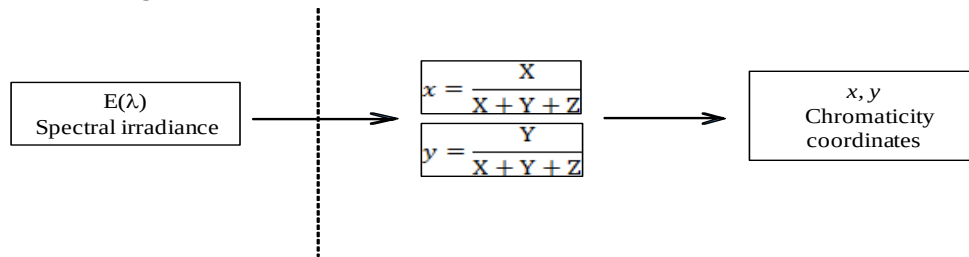


Fig. 4-22. Spectral irradiance as unique input quantity when estimating chromaticity coordinates uncertainty.

Thus, the uncertainty estimation of the spectral irradiance was done by considering the input and influence quantities presented in 오류! 참조 원본을 찾을 수 없습니다..

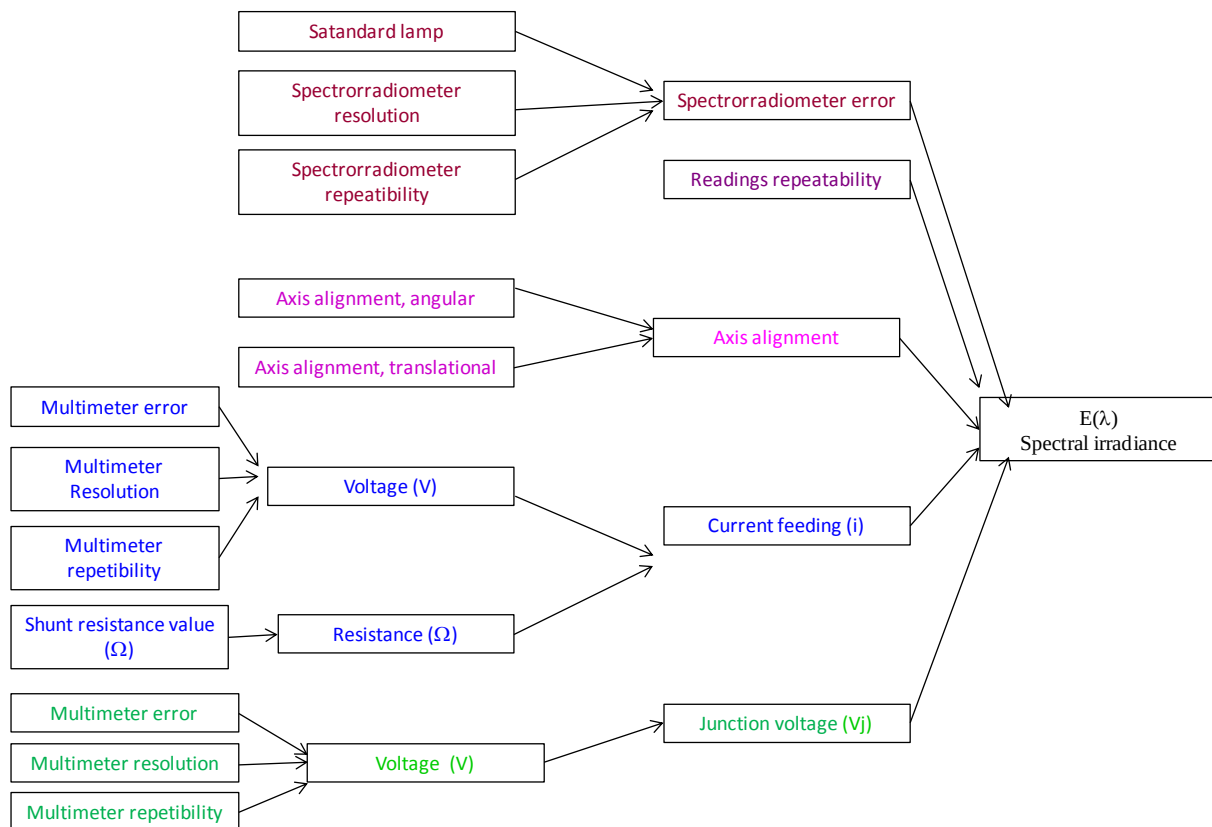


Fig. 4-23. Spectral irradiance uncertainty components in CENAM.

Table 4-40. CENAM uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Reading repeatability*	0.675	A	normal	1.000	0.675	11	O

	0.141			1.000	0.141		
Axis alignment	0.09	A	rectangular	1.00	0.09	4	O
	0.13			1.00	0.13		
Current feeding accuracy	0.25	A	rectangular	1.94	0.48	44	X
	0.48			0.22	0.11		
Junction voltage	0.08	A	rectangular	5.21	0.41	14	X
	0.15			0.60	0.09		
Propagation from spectral distribution measurement	15.66	B	normal	0.00002	0.0003	200	X
	13.96			0.00002	0.0003		
Combined standard uncertainty (%)	--	--	normal	--	0.9	33	--
					0.2	57	

Table 4-41. CENAM uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty y (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Reading repeatability*	0.435	A	normal	1	0.435	11	O
	0.361			1	0.361		
Axis alignment	0.04	A	rectangular	1	0.04	4	O
	0.10			1	0.10		
Current feeding accuracy	0.93	A	rectangular	0.12	0.11	44	X
	0.27			0.19	0.05		
Junction voltage	0.47	A	rectangular	0.78	0.37	14	X
	0.13			2.08	0.28		
Propagation from spectral distribution measurement	15.66	B	normal	0.00002	0.0003	200	X
	13.96			0.00002	0.0003		
Combined standard uncertainty (%)	--	--	normal	--	0.6	30	--
					0.5	23	

Table 4-42. CENAM uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty y (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Reading repeatability*	0.578	A	normal	1	0.578	11	O
	1.052			1	1.052		
Axis alignment	0.00	A	rectangular	1	0.00	4	O

	0.02			1	0.02		
Current feeding accuracy	1.60	A	rectangular	0.4	0.66	44	X
	2.54			0.5	1.26		
Junction voltage	0.42	A	rectangular	0.64640	0.27	14	X
	0.67			0.82200	0.55		
Propagation from spectral distribution measurement	15.66	B	normal	0.00002	0.0003	200	X
	13.96			0.00002	0.0003		
Combined standard uncertainty (%)	--	--	normal	--	0.9	72	--
					1.7	75	

Table 4-43. CENAM uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Reading repeatability*	0.014	A	normal	1	0.014	11	O
	0.017			1	0.017		
Axis alignment	0.04	A	rectangular	1	0.04	4	O
	0.05			1	0.05		
Current feeding accuracy	0.76	A	rectangular	0.1	0.06	44	X
	0.83			0.1	0.07		
Junction voltage	0.25	A	rectangular	0.02	0.01	14	X
	0.28			0.03	0.01		
Propagation from spectral distribution measurement	15.66	B	normal	0.00002	0.0003	200	X
	13.96			0.00002	0.0003		
Combined standard uncertainty (%)	--	--	normal	--	0.1	308	--
					0.1	366	

Table 4-44. CENAM uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Reading repeatability*	0.478	A	normal	1.000	0.478	11	O
	0.535			1.000	0.535		
Axis alignment	0.04	A	rectangular	1.00	0.04	4	O
	0.10			1.00	0.10		
Current feeding accuracy	0.93	A	rectangular	1.09	1.02	44	X

	0.34			3.15	1.07		
Junction voltage	0.35	A	rectangular	0.68	0.23	14	X
	0.13			1.94	0.24		
Propagation from spectral distribution measurement	15.66	B	normal	0.00002	0.0003	200	X
	13.96			0.00002	0.0003		
Combined standard uncertainty (%)	--	--	normal	--	1.2	179	--
					1.2	159	

Table 4-45. CENAM uncertainty budget of junction voltage measurement.

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Readings repeatability	0.00031	A	normal	1	0.00031	14	O
Multimeter error	0.00002	B	normal	1	0.00002	200	X
Multimeter resolution	0.00001	B	rectangular	1	0.00001	200	X
Combined standard uncertainty (%)	--	--	normal	--	0.009	14	--

4.7. LNE

4.7.1. Measurement setup

LNE has developed a measurement set-up to measure photometric and colorimetric characteristics of LEDs. This set-up is based on a goniophotometer designed to meet the requirements of the CIE127 standards for averaged intensity and total flux measurements. It is optimised for high power white LEDs measurements and was adapted for the LEDs in the framework of the APMP-S3 supplementary comparison. The schematic of the goniophotometer is shown on 오류! 참조 원본을 찾을 수 없습니다.. It is 2 m long and 1.8 m high.

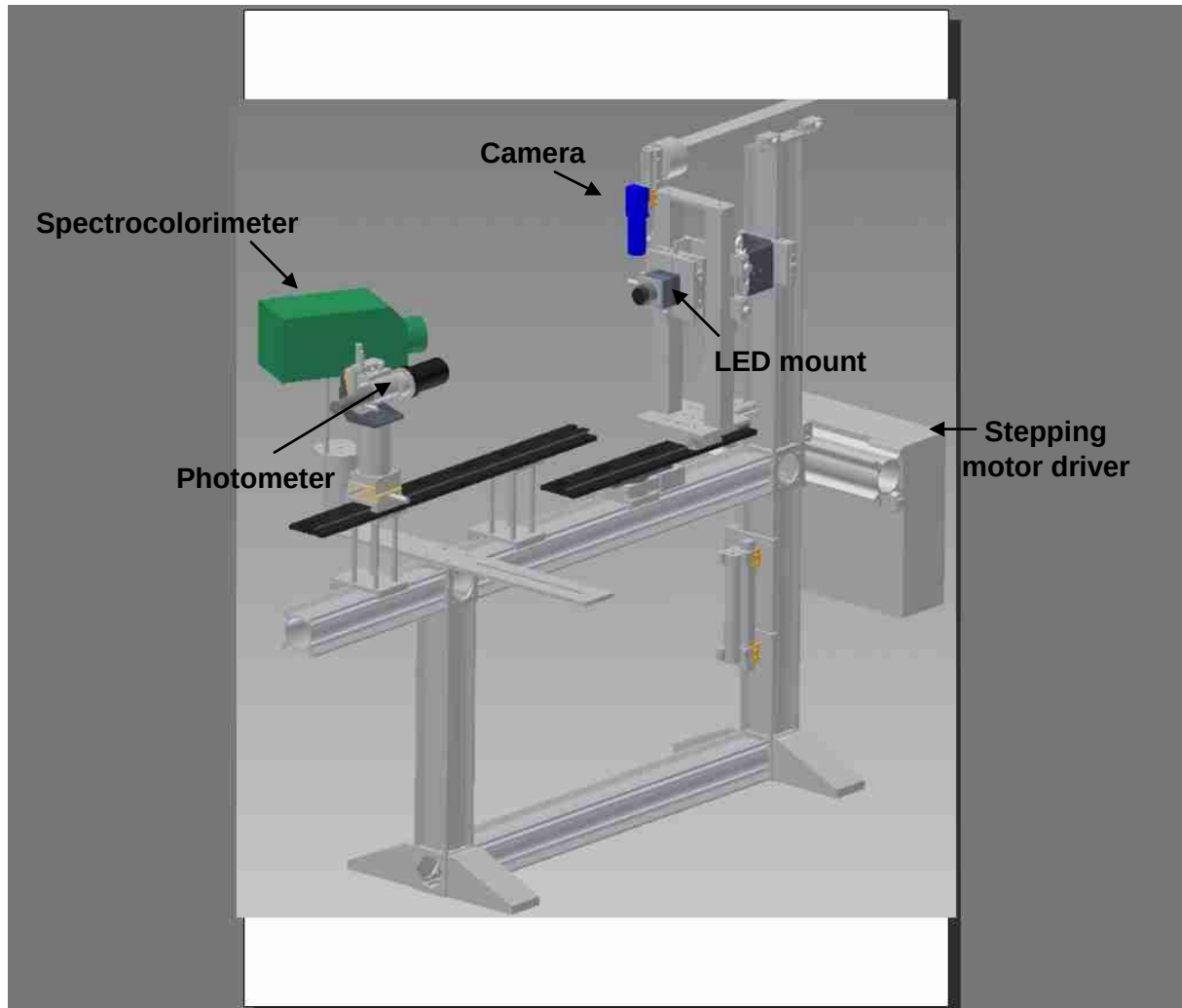


Fig. 4-24. Goniophotometer for LEDs flux measurements in LNE.

The set-up is made of the following parts :

- Optical rails to set the main frame
- A multi-axis LED mount which allow the accurate alignment of the LED along the horizontal optical axis and with respect to the photometric center of the goniophotometer. This device is mounted onto a horizontal axis motorised rotation stage that rotates the LED around the optical axis. A detailed schematic of the LED mount is shown on Fig. 4-25.
- A vertical axis motorised rotation stage on which the multi-axis LED mount is placed.

A camera placed above the LED allows us to adjust the position of the LED with respect to the photometric center. The photometer is mounted on an optical rail. The distance between the photometer and the LED can be adjusted to meet the requirements of the measurement conditions. During the measurements the photometer is kept steady. Laser beam is used to define the optical axis of the goniophotometer.

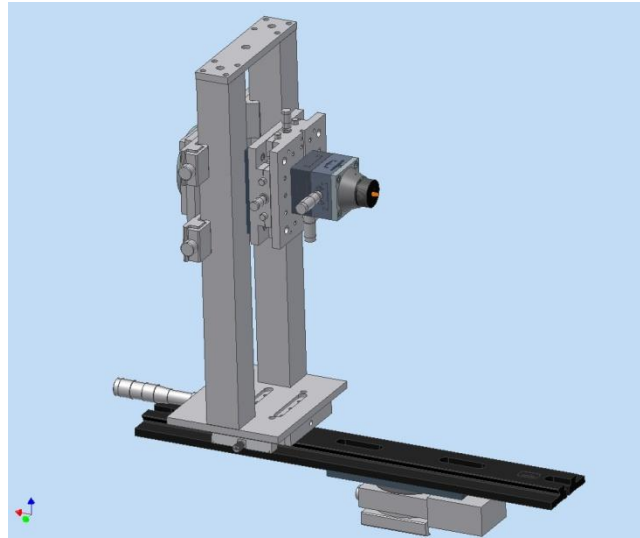


Fig. 4-25. LED mount in LNE.

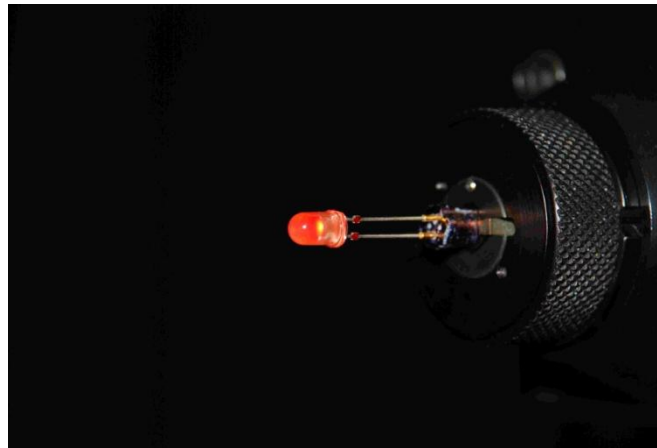


Fig. 4-26. LED holder in LNE.

The distance between the LED tip and the photometer is 100 mm (CIE 127, condition B). The instruments used to perform the measurements are listed in 오류! 참조 원본을 찾을 수 없습니다..

Table 4-46. Instruments used on the LED photometric bench in LNE.

Instrument	Manufacturer	Type	Function
Spectrocolorimeter	Minolta	CS1000	Colour measurement
LED power supply	Agilent	3436A	Stabilised LED power supply
Shunt resistor	AOIP	1000 Ω / 228RE6	LED current measurement
Multimeter	Hewlett-Packard	3457A	LED junction voltage measurement

4.7.2. Mounting and alignment

Colour measurements are performed following intensity measurements. The LED mount is rotated by 15° to align the LED with respect to the spectroradiometer as shown on Fig. 4-27.

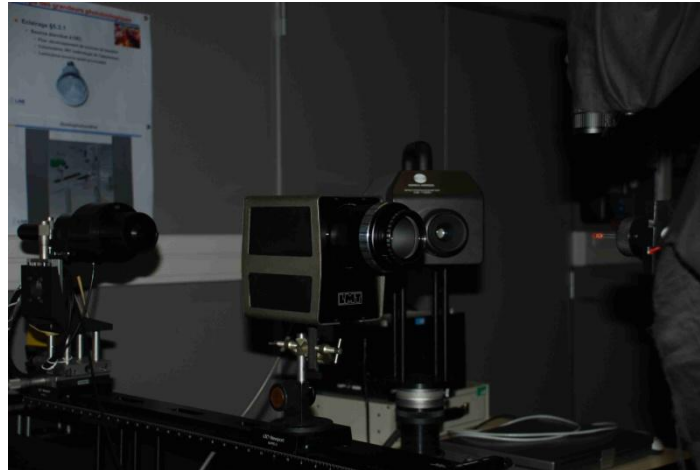


Fig. 4-27. Luminancemeter used to align the LED in LNE.

4.7.3. Traceability

Spectroradiometer

The spectroradiometer is calibrated in relative spectral radiance at LNE using an integrating sphere based radiance source itself calibrated against a set of three FEL type irradiance lamps at LNE-INM.

Electrical Instruments

All electrical instruments with critical impact on the measurements are calibrated by the LNE electrical department which is COFRAC (Comité Français d'Accréditation) accredited. COFRAC is the French accreditation body.

4.7.4. Measurement uncertainty

Color measurement

Reading repeatability

This uncertainty is estimated from the standard deviation of 5 measurements performed in the same operating conditions. The uncertainty associated to each colour are the following:

	LED type			
	Red	Green	Blue	White
x	0.020	0.035	0	0.16
y	0.050	0.010	0.080	0.05

Component due to axis alignment

This uncertainty is included in the reading repeatability.

Component due to current feeding accuracy.

The current is measured through a 1000 Ω resistor using a voltmeter. The resistor is calibrated with an uncertainty of $1 \cdot 10^{-5}$. The voltmeter is calibrated with an uncertainty of $1 \cdot 10^{-5}$. Therefore the current is measured with an uncertainty of $1.4 \cdot 10^{-5}$. The current is adjusted with an offset of ± 0.001 mA which corresponds to a relative error of $5 \cdot 10^{-5}$. The intensity is not corrected for this offset which is included in the uncertainty of the current. The overall uncertainty on the current feeding is obtained from the uncertainty due to the current measurement and the current offset, that is $5.2 \cdot 10^{-5}$. From the manufacturer's data sheets we estimate that this component can be neglected.

Component due to ambient temperature

The measurements are performed at $22 \text{ }^{\circ}\text{C} \pm 1 \text{ }^{\circ}\text{C}$. The measurement uncertainty due to the uncertainty on the ambient temperature is determined from the manufacturer's data sheets and modeling in the spectrum changes (wavelength shift). The results are summarized in the following table in percent:

	LED type			
	Red	Green	Blue	White
x	0.020	0.080	0.080	0.065
y	0.040	0.010	0.30	0.065

Component due to the calibration of the spectrophotometer in spectral response

The photometer is calibrated with a relative uncertainty of 0.6%.

Component due to linearity of the photometer

The relative spectral radiance measurement is performed with an uncertainty of 1.5%. The corresponding uncertainty on colour measurements are summarized in the following table in percent (based on computer simulation):

	LED type			
	Red	Green	Blue	White
x	0.030	0.80	0.27	0.80
y	0.070	0.070	1.1	1.3

Component due to wavelength scale calibration of the spectroradiometer

The wavelength scale of the spectroradiometer is calibrated with an uncertainty of 0.5 nm. The corresponding uncertainty on colour measurements is obtained from computer simulation and is shown in the following table in percent:

	LED type			
	Red	Green	Blue	White
x	0.080	0.90	0.46	0.0036
y	0.18	0.11	2.0	0.0032

Component due to spectral bandwidth of spectroradiometer

The uncertainty due to spectral bandwidth (5 nm FWHM) of the spectroradiometer is evaluated from computer simulation by broadening of the LED spectrum. The result is shown in the following table in percent:

	LED type			
	Red	Green	Blue	White
x	0.043	0.19	0.011	0.13
y	0.33	0.11	0.33	0.20

**Table 4-47. LNE uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R).
Upper values for x, lower values for y.**

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Reading repeatability	0.00014	A	t	1	0.00014	4	X
	0.00015			1	0.00015		
Current feeding accuracy (A)	0.000001	B	rectangular	0	0.00000	∞	X
	0.000001			0	0.00000		
Ambient temperature (°C)	1	B	rectangular	0.00014	0.00014	∞	X
	1			0.00012	0.00012		
Relative spectral response calibration	0.015	B	normal	0.014	0.00021	∞	O
	0.015			0.014	0.00021		

Wavelength accuracy (nm)	0.5	B	rectangular	0.00112	0.00056	∞	O
	0.5			0.00105	0.00053		
Spectral bandwidth	0.00028	B	rectangular	1	0.00028	∞	O
	0.00099			1	0.00099		
Combined standard uncertainty	--	--	normal		0.00069	∞	--
					0.0012		

Table 4-48. LNE uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Reading repeatability	0.00006	A	t	1	0.00006	4	X
	0.00007			1	0.00007		
Current feeding accuracy (A)	0.000001	B	rectangular	0	0.00000	∞	X
	0.000001			0	0.00000		
Ambient temperature (°C)	1	B	rectangular	0.00014	0.00014	∞	X
	1			0.00007	0.00007		
Relative spectral response calibration	0.015	B	normal	0.085	0.00128	∞	O
	0.015			0.033	0.00050		
Wavelength accuracy (nm)	0.5	B	rectangular	0.003	0.00150	∞	O
	0.5			0.0015	0.00075		
Spectral bandwidth	0.00030	B	rectangular	1	0.00030	∞	O
	0.00075			1	0.00075		
Combined standard uncertainty	--	--	normal		0.0020	∞	--
					0.0012		

Table 4-49. LNE uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Reading	0.00000	A	t	1	0.00000	4	X

repeatability	0.00006			1	0.00006		
Current feeding accuracy (A)	0.000001	B	rectangular	0	0.00000	∞	X
	0.000001			0	0.00000		
Ambient temperature (°C)	1	B	rectangular	0.00010	0.00010	∞	X
	1			0.00024	0.00024		
Relative spectral response calibration	0.015	B	normal	0.0215	0.00032	∞	O
	0.015			0.05	0.00075		
Wavelength accuracy (nm)	0.5	B	rectangular	0.0011	0.00055	∞	O
	0.5			0.003	0.00150		
Spectral bandwidth	0.00001	B	rectangular	1	0.00001	∞	O
	0.00025			1	0.00025		
Combined standard uncertainty	--	--	normal		0.00065	∞	--
					0.0017		

Table 4-50. LNE uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Reading repeatability	0.00050	A	t	1	0.00050	4	X
	0.00016			1	0.00016		
Current feeding accuracy (A)	0.000001	B	rectangular	0	0.00000	∞	X
	0.000001			0	0.00000		
Ambient temperature (°C)	1	B	rectangular	0.00020	0.00020	∞	X
	1			0.00020	0.00020		
Relative spectral response calibration	0.015	B	normal	0.16	0.00240	∞	O
	0.015			0.24	0.00360		
Wavelength accuracy (nm)	0.5	B	rectangular	0.00002	0.00001	∞	O
	0.5			0.00002	0.00001		
Spectral bandwidth	0.00040	B	rectangular	1	0.00040	∞	O
	0.00060			1	0.00060		

Combined standard uncertainty	--	--	normal		0.0025	∞	--
					0.0037		

Table 4-51. LNE uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Not submitted.

Junction Voltage

Repeatability

This uncertainty is estimated from the standard deviation of 20 measurements performed in the same operating conditions. For all type of LED the uncertainty is 0.02%.

Component due to the calibration of the voltmeter

The voltmeter used for the junction voltage measurement is calibrated with an uncertainty of 0.001 %.

Component due to position of junction voltage measurement point.

The leads of the LED are made of iron for the red LED and of copper for the green, blue and white LED. The 4-wires device used to measure the junction voltage is located 20 mm away from the LED chip. Taking into account the geometry of the leads (40 mm long and 0.25 mm² area) and the conductivity of the material used for the leads we determine the voltage drop due to the leads. The results are summarized in the following table.

LED type	Relative voltage drop @ 20 mA (%)
Red	0.008
Green	0.0008
Blue	0.0008
White	0.0008
Diffuser	0.0008

Table 4-52. LNE uncertainty budget of junction voltage measurement of red LEDs.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Repeatability	0.01	A	normal	1	0.01	19	X
Calibration of voltmeter	0.001	B	normal	1	0.001	∞	O

Junction position dependence*	0.008	B	rectangular	1	0.008	∞	X
Combined standard uncertainty (%)	--	--	normal	--	0.013	∞	--

Table 4-53. LNE uncertainty budget of junction voltage measurement of green, blue, white and diffuser-type LEDs.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Repeatability	0.01	A	normal	1	0.01	19	X
Calibration of voltmeter	0.001	B	normal	1	0.001	∞	O
Junction position dependence*	0.0008	B	rectangular	1	0.0008	∞	X
Combined standard uncertainty (%)	--	--	normal	--	0.010	∞	--

4.8. METAS

4.8.1. Measurement setup

The measurements are performed in two steps: First the spectro-radiometer is calibrated against a spectral irradiance standard (FEL 1000W). In the second step the spectra of the LED's are measured. As the diameter of the input integrating sphere (i.e. 10 mm) is different than the nominal condition ($\sqrt{100 \text{ mm}^2/\pi \cdot 4} = 11.28 \text{ mm}$) the measurement distance was adapted to 88.6 mm in order to collect the same angular part of the LED output. The measurements were taken between 380 nm and 780 nm with 2 nm steps.

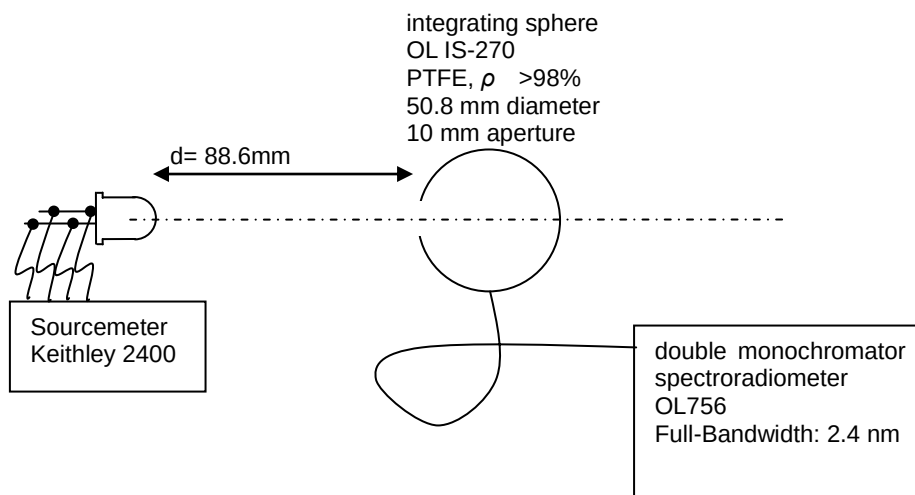


Fig. 4-28. Schematic setup for LED emission color in METAS.

4.8.2. Mounting and alignment

The LED is fixed inside a kinematic optical mount. The LED is connected through a "true" 4 wires connection. The voltage is measured at the end of the pin by gold plated electrical connectors (yellow and green wire in the image below). The current is feed through electrical clamps (brown and white wire).

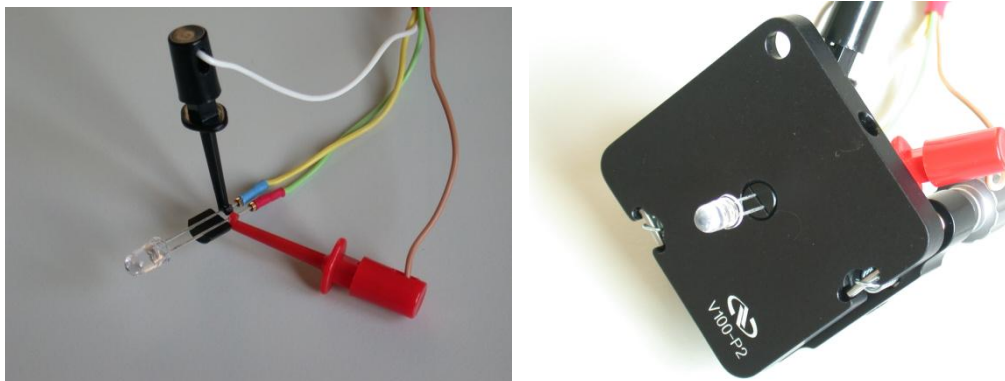
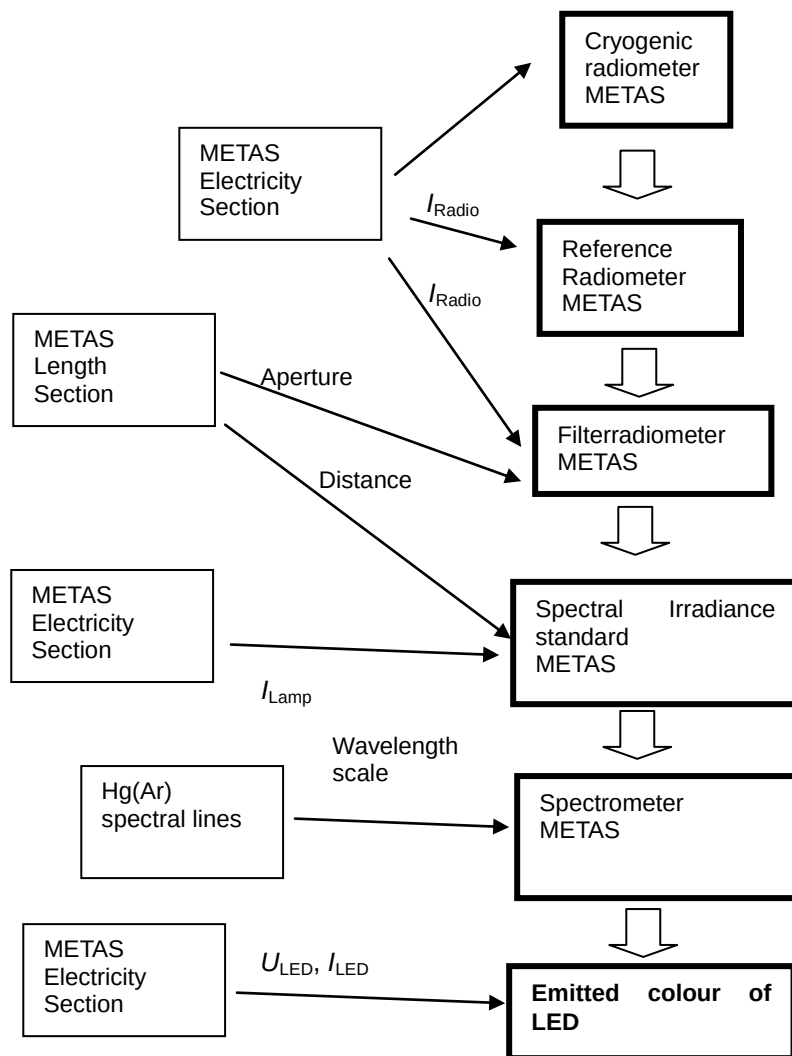


Fig. 4-29. LED mount and wire connection in METAS.

4.8.3. Traceability

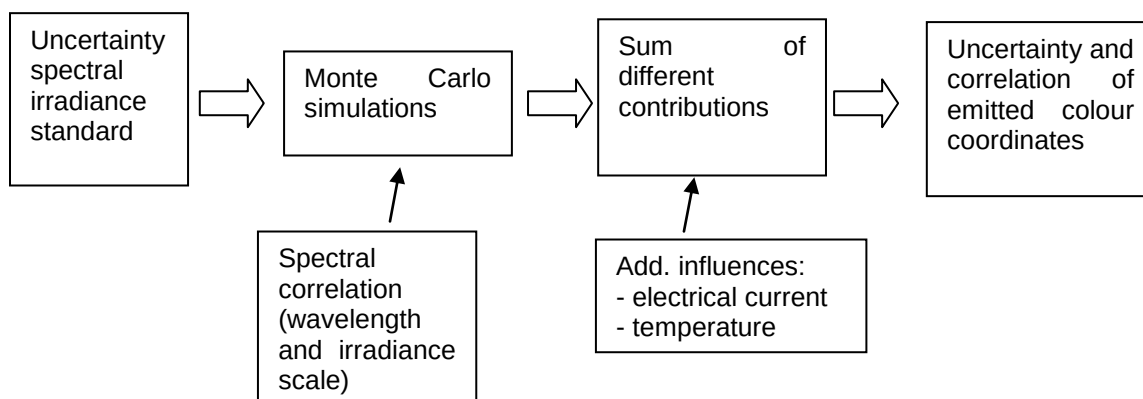
All primary quantities (i.e. illuminance, length, current, voltage etc) and secondary quantities (temperature, humidity, etc) are traceable to national standards realized at METAS. The detailed view of the traceability of the primary quantities is shown in the following diagram.



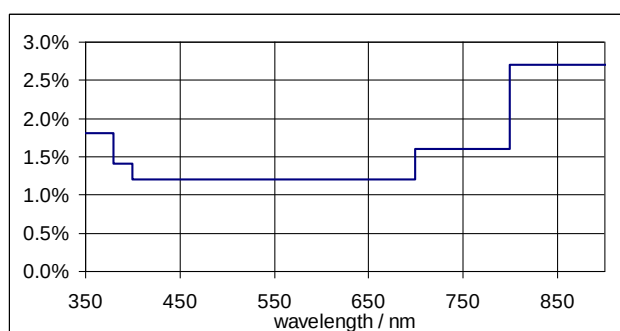
All primary quantities (i.e. illuminance, length, current, voltage etc) and secondary quantities (temperature, humidity, etc) are traceable to national standards realized at METAS. The detailed view of the traceability of the primary quantities is shown in the following diagram.

4.8.4. Measurement uncertainty

In contrast to the uncertainty evaluation of S3a and S3b, the uncertainty analysis of the chromaticity coordinates is based on Monte Carlo (MC) simulations. There are mainly two reasons for this: The correlation of the input quantities (mainly the wavelength scale) and the correlation of the output quantities (x , y) can easily be estimated without algebraic or analytical analysis. The procedure is outlined in the following diagram:



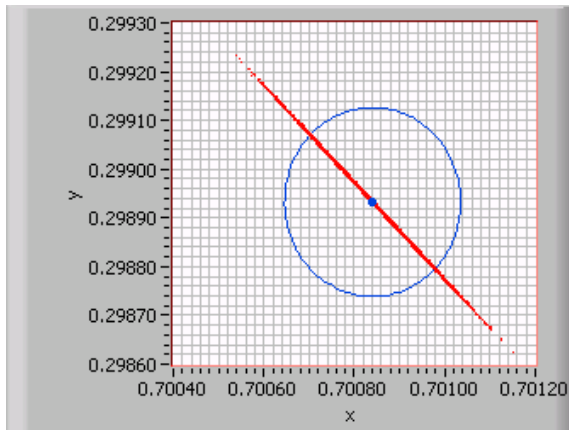
Starting point is the standard uncertainty ($k = 1$) of the spectral irradiance standard used for calibrating the double monochromator spectroradiometer:



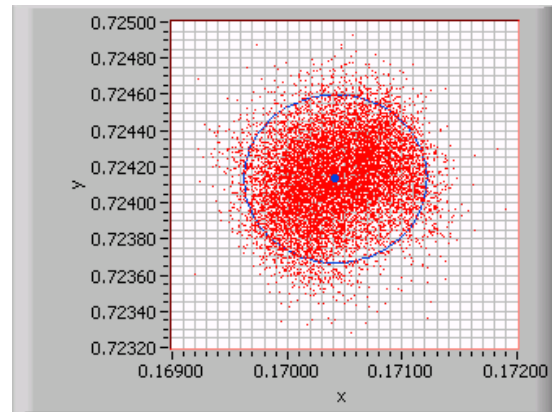
In the next step a set of typically 10,000 spectra is generated based on the measured spectral distribution of the DUT-LED and considering the different uncertainty contributions:

Quantity	Standard uncertainty, PDF	Correlations
Spectral irradiance scale	See figure above, PDF: normal distributed	uncorrelated
Wavelength scale	RPD with ± 0.2 nm	uncorrelated
Wavelength scale	RPD with ± 0.1 nm	Fully correlated (i.e. the whole wavelength scale is shifted left and right).

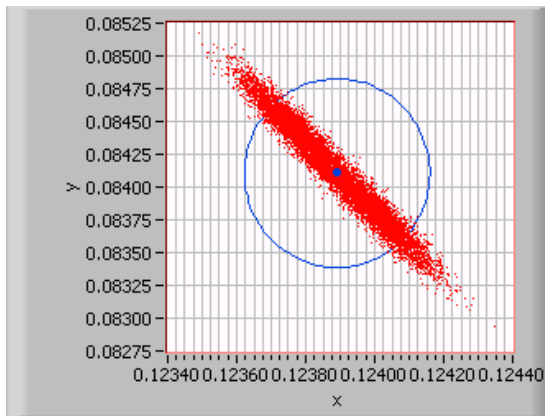
The resulting values of x and y are analyzed by statistical methods. The diagrams below show the typical output of the MC-simulation. The red dots are the (x,y) coordinates of an individual calculation. The blue ellipse shows the confidence region ($k = 2$) if the data points are considered fully uncorrelated.



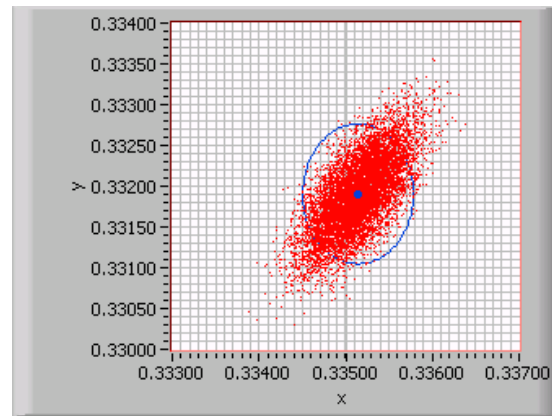
MC simulation of red LED (R-1)



MC simulation of green LED (G-1)



MC simulation of blue LED (B-1)



MC simulation of white LED (W-1)

It is obvious that in some cases (mainly red and blue coloured LED's) the quantities are strongly correlated. The correlation coefficients have typically the following values and are individually reported in the results sheet:

LED	Typical value of the correlation coefficient $r(x,y)$	correlation
R-1, R-2, R-3	$-0.99988 > r(x,y) > -1$	Fully correlated
G-1, G-2, G-3, D-1, D-2	$-0.3 < r(x,y) > 0.3$	Uncorrelated
B-1, B-2, B-3	$-0.98 > r(x,y) > -0.94$	Strongly correlated
W-1, W-2, W-3	$0.6 < r(x,y) < 0.8$	Slightly correlated

Influence of the electrical current on the colour coordinates:

Based on the datasheets of the LED's the uncertainty contributions of the electrical current on the colour coordinates has been estimated. The relative standard MU being $u(J_s) / J_s = 1 \times 10^{-4}$:

$u(J_s)=0.002\text{mA}$	$u(x)$	$u(y)$
R-1, R-2, R-3	1.6E-07	-1.6E-07
G-1, G-2, G-3, D-1, D-2	-3.6E-05	-4.2E-05
B-1, B-2, B-3	1.4E-06	-3.0E-06
W-1, W-2, W-3	-7.8E-07	-3.3E-06

Influence of the ambient temperature on the colour coordinates:

Based on the datasheets of the LEDs, the uncertainty contributions of the ambient temperature on the dominant wavelength and the colour coordinates has been estimated. The relative standard MU of the ambient temperature measurement being $u(T_{amb}) = (0.5 / \sqrt{3}) = 0.28$ °C.

$u(T_{amb})=0.28\text{ K}$	$\lambda_{\text{dom}} / \text{nm}$	$u(x)$	$u(y)$
R-1, R-2, R-3	0.022	3.5E-05	-3.5E-05
G-1, G-2, G-3, D-1, D-2	0.007	5.6E-05	5.6E-05
B-1, B-2, B-3	0.006	-1.6E-05	2.8E-05
W-1, W-2, W-3		-5.9E-05	-4.7E-05

These uncertainties are added to the uncertainties of the MC simulations. The following quantities were not considered:

- The influence of the ambient temperature uncertainty on the spectroradiometer as a temperature stabilized system was used.
- Spectral bandwidth effects of the spectroradiometer. The reported values are not corrected for the spectral bandpass function. The spectral bandwidth of the spectroradiometer is 2.4 nm.
- Fluorescence effects of the input sphere (PTFE), no data were available.
- Spectral straylight (double monochromator was used).
- ageing of the DUT as no relevant information was available.

Table 4-54. METAS uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Chromaticity coordinate from MC simulation*)	0.00022 0.00026	B	normal like	1	0.00022 0.00026		X
LED ambient temperature	0.28K	B	rectangular	1.25E-04 /K -1.25E-04 /K	3.5E-05 -3.5E-05		X
electrical current	0.002mA	B	normal	8e-5 / mA -8e-5 / mA	1.6E-07 -1.6E-07		X

Combined standard uncertainty	--	--	normal	--	0.00022 0.00026		--
--------------------------------------	----	----	---------------	----	--------------------	--	----

*) includes correlated and uncorrelated wavelength, relative spectral irradiance scale, reading

Table 4-55. METAS uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Chromaticity coordinate from MC simulation*)	0.00080 0.00046	B	normal like	1	0.00080 0.00045		X
LED ambient temperature	0.28K	B	rectangular	2E-04 /K 2E-04 /K	5.6E-05 5.6E-05		X
electrical current	0.002mA	B	normal	-1.8e-2 / mA -2.1e-2 / mA	-3.6E-05 -4.2E-05		X
Combined standard uncertainty	--	--	normal	--	0.00080 0.00046		--

*) includes correlated and uncorrelated wavelength, relative spectral irradiance scale, reading

Table 4-56. METAS uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Chromaticity coordinate from MC simulation*)	0.00026 0.00072	B	normal like	1	0.00026 0.00072		
LED ambient temperature	0.28K	B	rectangular	-5.7E-05 /K 1.0E-04 /K	-1.6E-05 2.8E-05		X
electrical current	0.002mA	B	normal	7e-4 / mA -1.5e-3 / mA	1.4E-06 -3.0E-06		X
Combined standard uncertainty	--	--	normal	--	0.00026 0.00072		--

*) includes correlated and uncorrelated wavelength, relative spectral irradiance scale, reading

Table 4-57. METAS uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Chromaticity coordinate from MC simulation*)	0.00081 0.00085	B	normal like	1	0.00081 0.00085		X
LED ambient temperature	0.28K	B	rectangular	-2.1E-04 /K 1E-04 /K	-5.9E-05 2.8E-05		X

electrical current	0.002mA	B	normal	7e-4 / mA -1.5e-3 / mA	1.4E-06 -3.0E-06		X
Combined standard uncertainty	--	--	normal	--	0.00081 0.00085		--

*) includes correlated and uncorrelated wavelength, relative spectral irradiance scale, reading

Table 4-58. METAS uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Chromaticity coordinate from MC simulation	0.0048**) 0.0039**)	B	NAN	1	0.0048 0.0039		X
LED ambient temperature	0.28K	B	rectangular	2E-04 /K 2E-04 /K	5.6E-05 5.6E-05		X
electrical current	0.002mA	B	normal	-1.8e-2 / mA -2.1e-2 / mA	-3.6E-05 -4.2E-05		X
Combined standard uncertainty	--	--	normal	--	0.0048 0.0039		--

*) includes correlated and uncorrelated wavelength, relative spectral irradiance scale, reading

**) the large standard uncertainty is due to the low signal to noise ratio of the reading

Model for junction voltage:

$$U_L = c_L \cdot c_C \cdot (1 + \alpha_{L,rel} \cdot (T_{aL} - T_{aL0})) \cdot (\bar{U}_{L1} - \bar{U}_{L0})$$

Description of terms:

U_L output quantity: junction voltage of the LED at certified conditions.

c_L = 1.0000, DVM calibration factor with absolute standard MU $u(c_L) = 1E-5$; Type B with DOF $\nu \rightarrow \infty$, no correlation.

c_C = 1.000, non-equivalence of the contact. We have tried different connectors. A spread in junction voltages have been observed even with 4 wires connections. The estimated absolute standard MU $u(c_C) = 0.0020$; Type B with DOF $\nu \rightarrow \infty$, no correlation.

$\alpha_{L,rel}$ = 0.000015, relative temp. coefficient according standard MU $u(\alpha_{L,rel}) = 5E-6$; Type B with DOF $\nu \rightarrow \infty$, no correlation.

T_{aL} = 22.6 °C, ambient temperature with $\pm 0.5^\circ\text{C}$ RPD, converted into standard MU $u(T_{aL}) = (0.5/\sqrt{3} = 0.29)^\circ\text{C}$; Type B with DOF $\nu \rightarrow \infty$, no correlation.

T_{aL0} = 23.0 °C, nominal ambient temperature, no uncertainty

$\bar{U}_{L1}$ = 1.94058 V, measured voltage (DVM), with standard MU of $u(\bar{U}_{L1}) = 0.00011$

V, 361 readings, Type A with DOF $\nu = 360$, no correlation.

$\bar{U}_{L0} = 0.00002$ V, measured zero voltage (DVM), with standard MU of $u(\bar{U}_{L1}) = 0.00011$ V, 361 readings, Type A with DOF $\nu = 360$, no correlation.

Table 4-59. METAS uncertainty budget of junction voltage measurement.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
DVM mean value voltage $\bar{U}_{L1}$	0.00011 V	A	t	0.99999 V/V	0.0055	360	X
DVM calibration factor c_L	1.0E-5	B	normal	1.94055 V	0.0010	∞	O
Relative temperature coefficient $\alpha_{L,rel}$	5.0E-6 K ⁻¹	B	normal	-0.77622 V/K	-0.0002	∞	X
Ambient temperature T_{aL}	0.29 °C	B	rectangular	0.00003 V/°C	0.0004	∞	X
Offset voltage $\bar{U}_{L0}$	0.00011 V	A	t	-0.99999 V/V	-0.0055	360	X
Non-equivalence of contact c_C	0.0021	B	rectangular	1.94055 V	0.21	∞	X
Combined standard uncertainty (V)	--	--	Normal	--	0.21	>1000	--

4.9. NMC-A*STAR

4.9.1. Measurement setup

The measurement setup of the averaged LED intensity is shown in Fig. 4-30 and Fig. 4-31. The LED light receptor is an integrating sphere with a 1 cm² opening input port according to the CIE requirement. The LED light received by the receptor is fed to a spectroradiometer (Model OL770 made by Optronic Laboratories) through an optical fibre. The spectroradiometer uses a cooled CCD detector with 128 x 1024 elements covering the wavelength range of 380 nm to 1100 nm. Its bandwidth (FWHM) is about 3.5 nm and the data interval is 1 nm.

The LED is driven by a programmable DC Source (Model 7651 made by Yokogawa). The driving current is measured using a calibrated precision resistor and a calibrated digital volt meter (Model 34420A made by Hewlett Packard). The electric connection in the LED holder is a 4-wire connection to achieve the accurate measurement of the LED forward voltage.

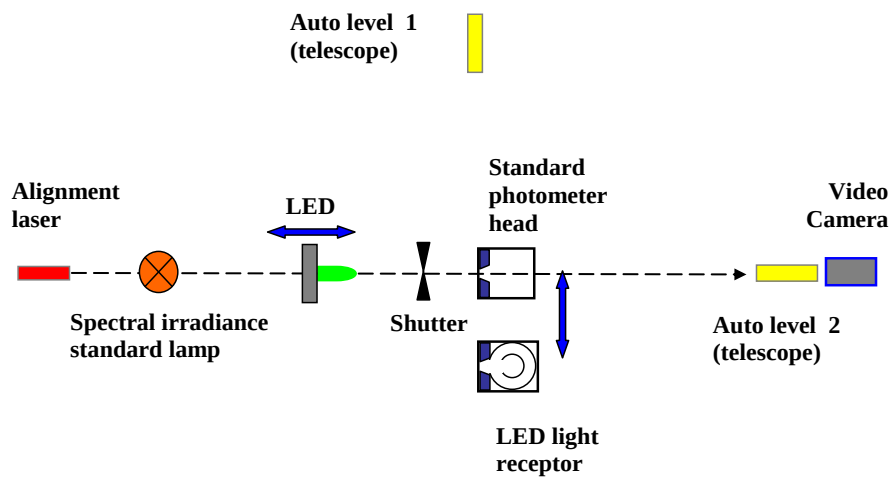


Fig. 4-30. LED averaged intensity measurement setup in A*STAR.

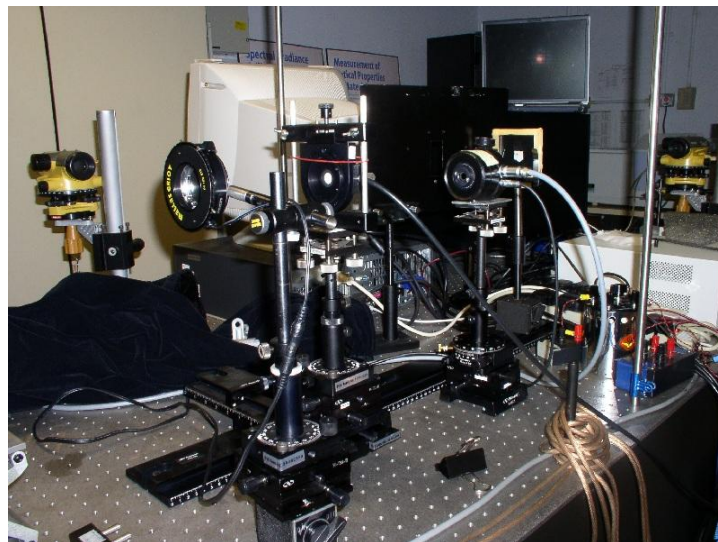
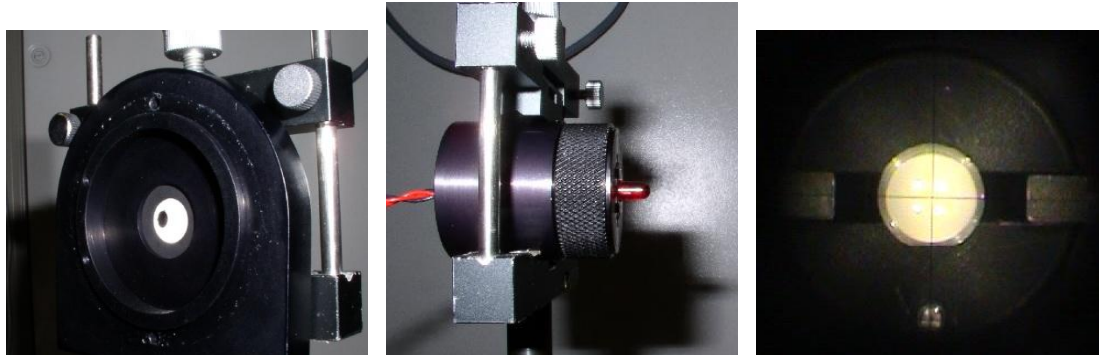


Fig. 4-31. Photograph of the LED averaged intensity measurement setup in A*STAR.

4.9.2. Mounting and alignment

Fig. 4-32 is a picture of the LED light receptor and Fig. 4-33 shows the LED holder.

**Fig. 4-32. LED receptor;****Fig. 4-33. LED holder;****Fig. 4-34. LED alignment in A*STAR.**

4.9.3. Traceability

The relative spectral responsivity of the spectroradiometer is calibrated by a spectral irradiance standard lamp traceable to NMC's spectral irradiance scale. The stray light error of the spectroradiometer is corrected using cut-on filters. The absolute luminous responsivity of the spectroradiometer is calibrated using a standard photometer traceable to NMC's luminous intensity scale. The average luminous intensity is used to calculate the emitted colour of the LED. The same data is also used to calculate the averaged luminous intensity by integrating (S3a).

4.9.4. Measurement uncertainty

Tables in the following are detailed uncertainty budgets of chromaticity coordinate measurement for the LEDs used in this APMP LED comparison.

The uncertainty evaluation is carried out according to Guide to the Expression of Uncertainty in Measurement (GUM). The artefact-dependent uncertainties shown in the table with * adopt the largest uncertainty values registered among the same type of LEDs measured. Expanded uncertainty are evaluated at a confidence level of approximately 95% with a coverage factor normally $k = 2$.

Table 4-60. A*STAR uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?#
Calibration of relative spectral irradiance of LED		B	normal	1	1.8E-5 1.8E-5	∞	Yes

LED axis alignment, angular	<i>Included in the component “Reproducibility” of three independent measurements.</i>						
LED axis alignment, translational	<i>Included in the component “Reproducibility” of three independent measurements.</i>						
Calibration of current feeding		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Scattered light including reflection from holder		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Wavelength scale of spectroradiometer*	0.2 nm	B	rectangular		1.7E-4 1.7E-4	∞	No
stray light and bandwidth correction of spectroradiometer (20 % of correction)*		B	rectangular	1	1.4E-4 1.4E-4	∞	No
Reproducibility		A	t	1	6.0E-5 6.0E-5	2	No
Combined standard uncertainty (%)	--	--	normal	--	2.3E-4 2.3E-4	439 439	--

Table 4-61. A*STAR uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated? #
Calibration of relative spectral irradiance of LED		B	normal	1	1.9E-4 2.0E-4	∞	Yes
LED axis alignment, angular	<i>Included in the component “Reproducibility” of three independent measurements.</i>						
LED axis alignment, translational	<i>Included in the component “Reproducibility” of three independent measurements.</i>						
Calibration of current feeding		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Scattered light including reflection from holder		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Wavelength scale of spectroradiometer*	0.2 nm	B	rectangular		6.5E-4 3.7E-4	∞	No
stray light and bandwidth correction of spectroradiometer (20 % of correction)*		B	rectangular	1	5.1E-4 1.1E-3	∞	No
Reproducibility		A	t	1	1.0E-4 6.0E-5	2	No
Combined standard uncertainty (%)	--	--	normal	--	8.5E-4 1.2E-3	>500 >500	--

Table 4-62. A*STAR uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated? #
Calibration of relative spectral irradiance of LED		B	normal	1	8.1E-5 4.0E-4	∞	Yes
LED axis alignment, angular	<i>Included in the component "Reproducibility" of three independent measurements.</i>						
LED axis alignment, translational	<i>Included in the component "Reproducibility" of three independent measurements.</i>						
Calibration of current feeding		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Scattered light including reflection from holder		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Wavelength scale of spectroradiometer*	0.2 nm	B	rectangular		2.5E-4 6.7E-4	∞	No
stray light and bandwidth correction of spectroradiometer (20 % of correction)*		B	rectangular	1	1.0E-4 5.8E-5	∞	No
Reproducibility		A	t	1	3.0E-5 9.0E-5	2	No
Combined standard uncertainty (%)	--	--	normal	--	2.9E-4 7.9E-4	>500 >500	--

Table 4-63. A*STAR uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated? #
Calibration of relative spectral irradiance of LED		B	normal	1	3.0E-4 3.7E-4	∞	Yes
LED axis alignment, angular	<i>Included in the component "Reproducibility" of three independent measurements.</i>						
LED axis alignment, translational	<i>Included in the component "Reproducibility" of three independent measurements.</i>						
Calibration of current feeding		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Scattered light including reflection from holder		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Wavelength scale of spectroradiometer*	0.2 nm	B	rectangular		2.3E-4 3.2E-4	∞	No
stray light and bandwidth correction of spectroradiometer (20 % of correction)*		B	rectangular	1	2.5E-4 4.2E-4	∞	No
Reproducibility		A	t	1	2.9E-4 2.4E-4	2	No

Combined standard uncertainty (%)	--	--	normal	--	5.4E-4 6.9E-4	24 138	--
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Table 4-64. A*STAR uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated? #
Calibration of relative spectral irradiance of LED		B	normal	1	1.9E-4 2.0E-4	∞	Yes
LED axis alignment, angular	Included in the component "Reproducibility" of three independent measurements.						
LED axis alignment, translational	Included in the component "Reproducibility" of three independent measurements.						
Calibration of current feeding		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Scattered light including reflection from holder		B	rectangular	1	5.8E-6 5.8E-6	∞	Yes
Wavelength scale of spectroradiometer*	0.2 nm	B	rectangular		6.5E-4 3.7E-4	∞	No
stray light and bandwidth correction of spectroradiometer (20 % of correction)*		B	rectangular	1	5.1E-4 1.1E-3	∞	No
Reproducibility		A	t	1	5.0E-4 1.0E-3	2	No
Combined standard uncertainty (%)	--	--	normal	--	9.8E-4 1.5E-3	30 11	--

오류! 참조 원본을 찾을 수 없습니다. is the detailed uncertainty budget of the junction voltage measurement, representatively presented for the red LEDs. The artefact-dependent uncertainties shown in the table with * adopt the largest uncertainty values registered among the same type of LEDs measured.

Table 4-65. A*STAR uncertainty budget of junction voltage measurement.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (V)	Deg. of freedom	Correlated?
Calibration of DVM		B	normal	1	9.5E-5	∞	Yes
Position of junction (0.05 Ω)		B	rectangular	1	5.78E-4	∞	No
Drift of junction voltage		B	rectangular	1	1.73E-4	∞	No

Reproducibility*		A	t	1	7.64E-4	5	No
Combined standard uncertainty (V)	--	--	normal	--	9.8E-4	13	--

4.10. NMIA¹⁰

4.10.1. Measurement setup

The relative spectral intensity was measured using an array spectrometer. One end of an optical fibre was placed next to, and behind, the precision aperture and directed towards the LED, the other end of the fibre was connected directly to the spectrometer.

4.10.2. Mounting and alignment

Each LED was mounted in a custom made aluminium LED mount with the front surface of the mount painted with spectrally non-selective gloss black paint. A separate aluminium base was provided for the diffused LEDs.

Each aluminium mount was set up to be within 0.1° of perpendicular to the measurement axis of the receiving radiometer by using a laser/mirror alignment technique. Since the flanged LEDs are not parallel sided, orthogonality of the LEDs relied upon the orthogonality of the LED base flange to the measurement axis. A value of $\pm 0.5^\circ$ was used for uncertainty calculations, allowing for imperfections in each diode for these LEDs.

For the diffused diodes, which were not flanged, the aluminium mount provided a close fit to the parallel sides of the diode, again $\pm 0.5^\circ$ was allowed for uncertainty calculations.

Each LED aluminium base was fitted to a standard kinematic mount and placed on the receiving kinematic base on top of a special carriage having five degrees of freedom in its physical adjustments as shown in Fig. 4-35.

¹⁰ The technical report and uncertainty budgets of NMIA are not reviewed by the participants due to the delayed submission.

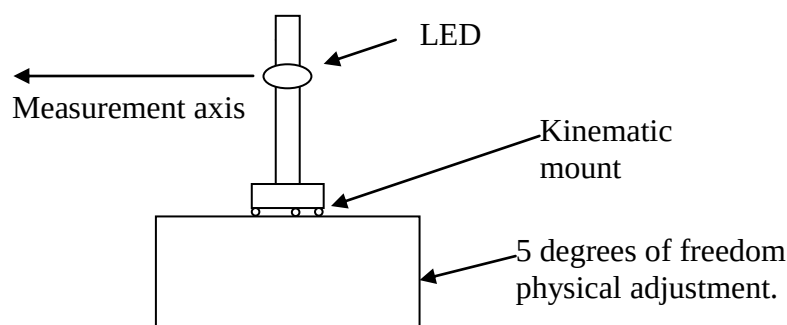


Fig. 4-35. Side view diagram of measurement setup in NMIA showing the LED mounted in the aluminium mount supported by a carriage having five degrees of freedom in physical adjustment.

The LEDs were held in place by a cylindrical nylon spacer with two holes running parallel to the centre of the cylinder, allowing the legs of the LED to pass through the spacer. The spacer was held in place using a copper side spring as shown in Fig. 4-36.

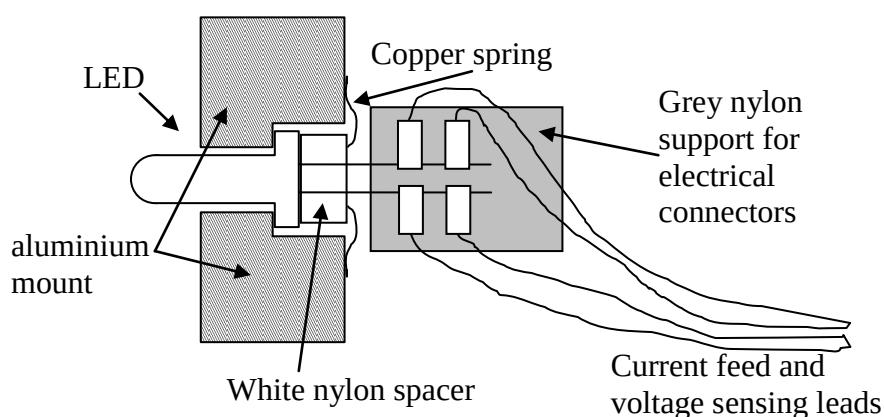


Fig. 4-36. Top view, cross-section diagram of LED mount in NMIA, showing the nylon spacer located by the copper spring, and including the grey nylon mount via which electrical connections were made.

The legs of the LED were inserted into a grey nylon mount containing four screw tensioned gold contacts via which the LED current was supplied and the LED potential was measured.

A temperature probe was attached to the aluminium base using aluminium tape to provide reasonable thermal contact. This provided a cross-check on the LED base temperature.

The detector system used was based on a calibrated Hamamatsu S6337 windowless silicon photodiode mounted behind a round 100 mm² area polished steel aperture with

aperture lands at a 60° angle to the measurement axis. The area surrounding the aperture was covered using a shield plate having a diffuse black spectrally non-selective paint to reduce inter-reflection between the LED mount and the aperture as shown in Fig. 4-37.

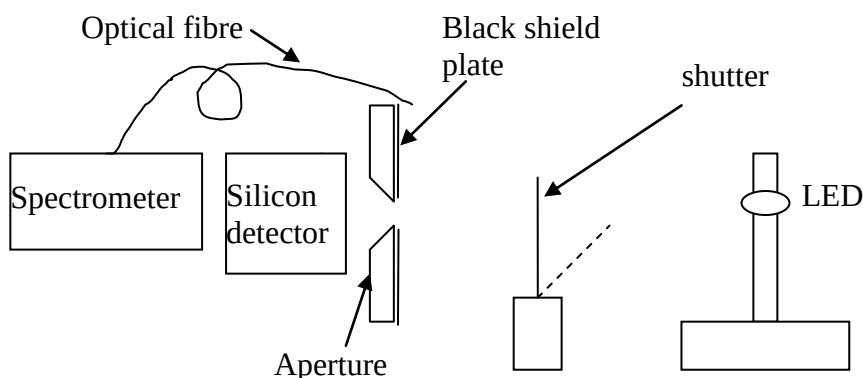


Fig. 4-37. Diagram of the detection system with precision steel aperture masked by blackened cover, optical fibre fed spectrometer and shutter.

A small area shutter was placed between the LED and the detector aperture to allow the stray light level to be recorded as far as possible. This was later subtracted from the signal level.

The detector was mounted on an X-Y scanning stage with a resolution of $2\ \mu\text{m}$.

The detector was aligned with the LED centre by using a bench telescope with a ring sight aligned along the measurement axis.

The separation between the tip of each LED and the plane of the detector aperture was determined using a calibrated vernier mounted telescope with an optical axis perpendicular to the measurement axis. The vernier resolution for this telescope was $0.01\ \text{mm}$.

The shutter did not restrict light entering the optical fibre and so the electronic dark level (internal to the spectrometer) was used for the dark level of the spectrometer. The optical fibre was aligned to point directly at the LED by finding the maximum signal.

For each LED the spatial uniformity of the irradiance output from the LED was measured over approximately $\pm 20\ \text{mm}$ around the central measurement position in order to determine uncertainties due to spatial and angular variation.

4.10.3. Traceability

The spectrometer was calibrated using NMIA colour standard source FEL6. This source

was calibrated for relative spectral irradiance directly against a blackbody (RN46736, dated 13 July 2004) at the same time, and using the same method, as for the lamps NMIA used in the CCPR K1-a 2005 Spectral Irradiance Key Comparison. Further details of the traceability of the relative spectral irradiance of lamp FEL6 can be found in the final report of this comparison.

4.10.4. Measurement uncertainty

The relative spectral irradiance measurements described in section S3a and used to calculate the response of the detector, were also used to calculate the CIE 1931 x, y chromaticity coordinates for each LED. As was described above, there were at least 30 measurements for each LED, allowing a value for the experimental standard deviation of the mean to be calculated for both x and y coordinates. These are listed in the tables as 'Reading repeatability' component.

A number of measurements were done to determine the variation of chromaticity coordinates due to angular alignment. With a difference of approximately 30° (corresponding to the angle between the optical fibre to the spectrometer and the alignment axis), the largest variation measured was of the order 0.0003 in both x and y. Thus a value of ± 0.00015 was used as the standard uncertainty for both coordinates.

The effect on measured chromaticity due to translational alignment was not investigated and was assumed negligible.

There was no observable correlation between measured feed current and chromaticity coordinate (both for x and y), and so no sensitivity coefficient could be determined. Thus the uncertainty component due to current feed accuracy was taken to be zero (and most likely absorbed by the reading repeatability component estimate).

Finally, a detailed analysis of the spectrometer and subsequent calculation of chromaticity coordinates has been performed previously. The standard uncertainty used by NMIA for our system is a value of ± 0.00033 for both chromaticity coordinates.

Table 4-66. NMIA uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Reading repeatability	0.0010 0.0002	A	t	1	0.001 0.0002	30	X

Axis alignment, angular	0.00015 0.00015	B	rectangular	1	0.00015 0.00015	100	X
Axis alignment, translational	0.0 0.0	B	rectangular	1	0.0 0.0	100	X
Current feeding accuracy	0.0 0.0	B	rectangular	1	0.0 0.0	100	O
Propagation from spectral distribution measurement	0.00033 0.00033	B	normal	1	0.00033 0.00033	100	O
Combined standard uncertainty	--	--	normal	--	0.0021 0.0008	∞	--

Table 4-67. NMIA uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Reading repeatability	0.0002 0.0003	A	t	1	0.0002 0.0003	30	X
Axis alignment, angular	0.00015 0.00015	B	rectangular	1	0.00015 0.00015	100	X
Axis alignment, translational	0.0 0.0	B	rectangular	1	0.0 0.0	100	X
Current feeding accuracy	0.0 0.0	B	rectangular	1	0.0 0.0	100	O
Propagation from spectral distribution measurement	0.00033 0.00033	B	normal	1	0.00033 0.00033	100	O
Combined standard uncertainty	--	--	normal	--	0.0008 0.0009	∞	--

Table 4-68. NMIA uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Reading repeatability	0.0001 0.0001	A	t	1	0.0001 0.0001	30	X
Axis alignment, angular	0.00015 0.00015	B	rectangular	1	0.00015 0.00015	100	X
Axis alignment, translational	0.0 0.0	B	rectangular	1	0.0 0.0	100	X
Current feeding accuracy	0.0 0.0	B	rectangular	1	0.0 0.0	100	O
Propagation from spectral distribution measurement	0.00033 0.00033	B	normal	1	0.00033 0.00033	100	O

Combined standard uncertainty	--	--	normal	--	0.0007 0.0007	∞	--
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Table 4-69. NMIA uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Reading repeatability	0.0001 0.0001	A	t	1	0.0001 0.0001	30	X
Axis alignment, angular	0.00015 0.00015	B	rectangular	1	0.00015 0.00015	100	X
Axis alignment, translational	0.0 0.0	B	rectangular	1	0.0 0.0	100	X
Current feeding accuracy	0.0 0.0	B	rectangular	1	0.0 0.0	100	O
Propagation from spectral distribution measurement	0.00033 0.00033	B	normal	1	0.00033 0.00033	100	O
Combined standard uncertainty	--	--	normal	--	0.0007 0.0007	∞	--

Table 4-70. NMIA uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Reading repeatability	0.0001 0.0001	A	t	1	0.0001 0.0001	30	X
Axis alignment, angular	0.00015 0.00015	B	rectangular	1	0.00015 0.00015	100	X
Axis alignment, translational	0.0 0.0	B	rectangular	1	0.0 0.0	100	X
Current feeding accuracy	0.0 0.0	B	rectangular	1	0.0 0.0	100	O
Propagation from spectral distribution measurement	0.00033 0.00033	B	normal	1	0.00033 0.00033	100	O
Combined standard uncertainty	--	--	normal	--	0.0007 0.0007	∞	--

Table 4-71. NMIA uncertainty budget of junction voltage measurement (typical).

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Calibration of voltmeter	0.001	B	normal	1	0.001	100	O
Junction position dependence	0.0035	B	rectangular	1	0.0035	100	X
Reproducibility	0.0001	A	normal	1	0.0001	30	X
Combined standard uncertainty (%)	--	--	normal	--	0.0036	116	--

4.11. NIST

4.11.1. Measurement setup

The measurement of LED color was based on the NIST spectral irradiance scale¹¹. The measurement setup used for this measurement is depicted in Fig. 4-38. A CCD-array spectroradiometer with a bandpass of approximately 3 nm (FWHM) and the spectral range from 350 nm to 1020 nm was used for this measurement. A 50 mm polytetrafluoroethylene (PTFE) based integrating sphere, with a circular entrance aperture of Ø11.3 mm (100 mm² in area) was used as the input optic of the spectroradiometer through an optical fiber bundle. Before the measurement of the test LEDs, the measurement system was calibrated against two standard spectral irradiance FEL lamps for spectral irradiance responsivity. The standard spectral irradiance FEL lamp was placed 0.5 m away from the Ø11.3 mm entrance aperture, and was aligned so that its optical axis intersected, perpendicularly, at the center of the Ø11.3 mm entrance aperture. The two standard lamps were calibrated in the direction of its optical axis for absolute spectral irradiance at 0.5 m in the NIST FASCAL¹¹.

¹¹ J. H. Walker, R. D. Saunders, J. K. Jackson, and D. A. McSparron, Spectral Irradiance Calibrations, NBS Special Publication 250-20. (1987) / Yoon H. W., Gibson C. E., and Barnes P. Y., Realization of the National Institute of Standards and Technology detector-based spectral irradiance scale, *Appl. Opt.* 41, 5879-5890. (2002)

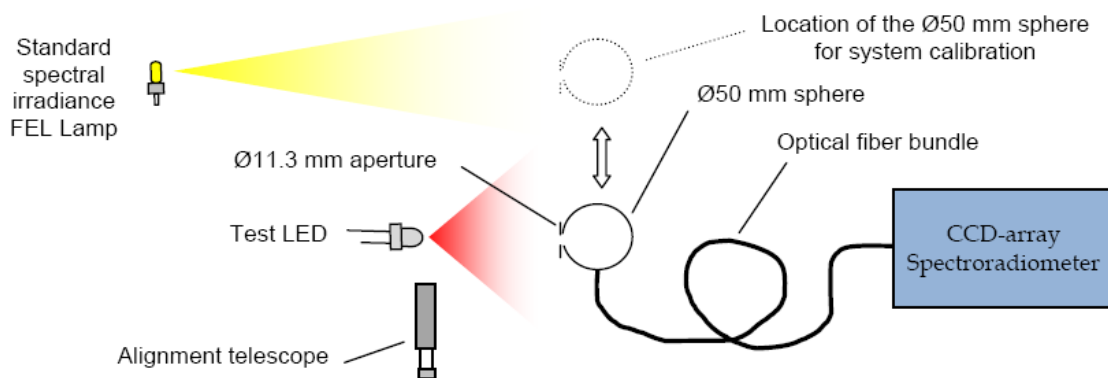


Fig. 4-38. Setup for measurement of LEDs for the CIE 1931 chromaticity coordinates x and y in NIST.

The test LED was operated on DC power at a constant current of 20 mA using a four-wire connection. The wiring diagram for this measurement is shown in Fig. 4-39. The operating current of the LED was measured with an 8.5 digit multimeter. The test LED was measured after it was powered on for 10 minutes. The output spectral signal of the spectroradiometer was recorded together with the LED current, LED voltage, room temperature, and room humidity. Corrections were applied for spectroradiometer's dark signal, the integrating-time nonlinearity, the signal-level nonlinearity, and the spectral stray light¹² to calculate the spectral irradiance of the test LED. The fluorescence of the 50 mm integrating sphere was checked to be negligible, thus no correction was applied. Each LED was measured for a total of two lightings (with two measurements for each lighting) to check its repeatability and reproducibility. The mean value of the CIE 1931 chromaticity coordinates, x and y , calculated from each measurement was reported, and the variation was included in the uncertainty budget of the measurement.

The measurement system was checked after the completion of all the measurements of the test LEDs, and the change or drift of the system was found to be negligible.

¹² Zong Y., Brown S. W., Johnson B. C., Lykke K. R., and Ohno Y., Simple spectral stray light correction method for array spectroradiometers, *Appl. Opt.*, 45, 1111-1119. (2006)

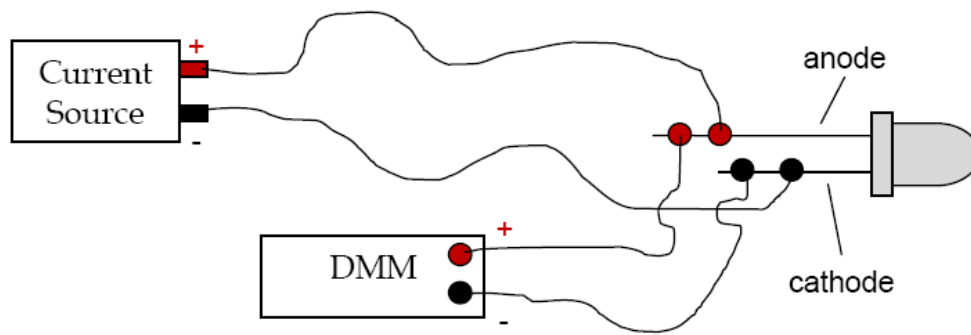


Fig. 4-39. Wiring diagram for measurement of a test LED in NIST.

4.11.2. Mounting and alignment

The test LED was mounted on a four-wire LED socket fixed on a long cylindrical metal tube. A photograph of a mounted LED is shown in Fig. 4-40. The test LED was aligned according to the standard condition B defined by the CIE for measurement of Averaged Luminous LED Intensity. Each LED was aligned so that its front tip was at 100 mm away from the $\varnothing 11.3$ mm entrance aperture of the 50 mm integrating sphere and thus the measurement solid angle was 0.01 sr. The geometric axis of the LED intersected, perpendicularly, at the center of the $\varnothing 11.3$ mm aperture. The alignment of the test LED for angle, position, and the distance was done by using a telescope shown in Fig. 4-41. The cone-shaped, specular black surface behind the test LED was for eliminating the inter-reflection between the 50 mm integrating sphere and the LED mount and also for preventing backward LED light from entering into the 50 mm integrating sphere.



Fig. 4-40. Photograph of an LED mounted on the cylindrical LED mount in NIST.

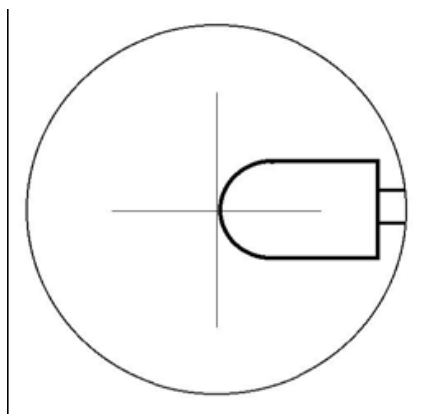


Fig. 4-41. View in the telescope showing the LED tip aligned to the right position and the LED mechanical axis aligned with the optical axis of the photometry bench.

4.11.3. Traceability

The two standard spectral irradiance FEL lamps used to calibrate the measurement system shown in Fig. 4-38 were calibrated in the NIST FASCAL for spectral irradiance at a distance of 0.5 m. The NIST spectral irradiance scale is derived from the NIST spectral irradiance responsivity scale, which is maintained on a group of trap detectors that are periodically calibrated against the NIST Reference Cryogenic Radiometer - Primary Optical Watt Radiometer (POWR).

4.11.4. Measurement uncertainty

The uncertainty budgets for measurement of CIE 1931 chromaticity coordinates, x and y , of the red, green, blue, white, and diffuser-type green LEDs are shown in the tables below, and the uncertainty budget for measurement of junction voltage of the test LEDs is shown in Table 4-77. The NIST policy on uncertainty statements is described in Reference¹³.

¹³ B. N. Taylor, and C. E. Kuyatt, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Technical Note 1297. (1993)

**Table 4-72. NIST uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R).
Upper values for x, lower values for y.**

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Degrees of freedom	Correlated?
NIST standard spectral irradiance FEL lamp	0.00002 0.00002	B	Normal	1	0.00002 0.00002	∞	Yes
Instrument wavelength error	0.00007 0.00007	B	Rectangular	1	0.00007 0.00007	∞	Yes
Instrument bandpass (nm)	3	B	Rectangular	0.00003	0.00009 0.00009	∞	Yes
Instrument residual signal-level nonlinearity	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
Instrument residual spectral stray light	0.00005 0.00005	B	Normal	1	0.00005 0.00005	∞	Yes
Instrument calibration against standard spectral irradiance FEL lamps	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
LED alignment: angle of LED's geometric axis	0.00005 0.00005	A	Normal	1	0.00005 0.00005	∞	No
LED alignment: position of LED's geometric axis	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED alignment: distance from the LED's front tip to the entrance aperture	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED current (%)	0.01	B	Normal	0.001	0.00001 0.00001	1	Yes
LED ambient temperature (°C)*	0.58	B	Rectangular	0.00004	0.00002 0.00002	∞	Yes
LED repeatability and reproducibility	0.00005 0.00005	A	Normal	1	0.00005 0.00005	3	No
Combined standard uncertainty			Normal		0.00015 0.00015	215 214	

*The sensitivity coefficient is based on typical values for LEDs of this type.

Table 4-73. NIST uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Degrees of freedom	Correlated?
NIST standard spectral irradiance FEL lamp	0.00010 0.00010	B	Normal	1	0.00010 0.00010	∞	Yes
Instrument wavelength error	0.00021 0.00021	B	Rectangular	1	0.00021 0.00021	∞	Yes
Instrument bandpass (nm)	3	B	Rectangular	0.00003	0.00009 0.00009	∞	Yes
Instrument residual signal-level nonlinearity	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
Instrument residual spectral stray light	0.00040 0.00040	B	Normal	1	0.00040 0.00040	∞	Yes
Instrument calibration against standard spectral irradiance FEL lamps	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
LED alignment: angle of LED's geometric axis	0.00005 0.00005	A	Normal	1	0.00005 0.00005	∞	No
LED alignment: position of LED's geometric axis	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED alignment: distance from the LED's front tip to the entrance aperture	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED current (%)	0.01	B	Normal	0.001	0.00001 0.00001	1	Yes
LED ambient temperature (°C)*	0.58	B	Rectangular	0.00004	0.00002 0.00002	∞	Yes
LED repeatability and reproducibility	0.00005 0.00005	A	Normal	1	0.00005 0.00005	3	No
Combined standard uncertainty			Normal		0.00048 0.00048	2.5×10^4 2.4×10^4	

*The sensitivity coefficient is based on typical values for LEDs of this type.

Table 4-74. NIST uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Degrees of freedom	Correlated?
NIST standard spectral irradiance FEL lamp	0.00003 0.00008	B	Normal	1	0.00003 0.00008	∞	Yes
Instrument wavelength error	0.00015 0.00022	B	Rectangular	1	0.00015 0.00022	∞	Yes
Instrument bandpass (nm)	3	B	Rectangular	0.00003	0.00009 0.00009	∞	Yes
Instrument residual signal-level nonlinearity	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
Instrument residual spectral stray light	0.00010 0.00010	B	Normal	1	0.00010 0.00010	∞	Yes
Instrument calibration against standard spectral irradiance FEL lamps	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
LED alignment: angle of LED's geometric axis	0.00005 0.00005	A	Normal	1	0.00005 0.00005	∞	No
LED alignment: position of LED's geometric axis	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED alignment: distance from the LED's front tip to the entrance aperture	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED current (%)	0.01	B	Normal	0.001	0.00001 0.00001	1	Yes
LED ambient temperature (°C)*	0.58	B	Rectangular	0.00005 0.00015	0.00003 0.00009	∞	Yes
LED repeatability and reproducibility	0.00005 0.00005	A	Normal	1	0.00005 0.00005	3	No
Combined standard uncertainty			Normal		0.00022 0.00029	1.1×10^3 3.5×10^3	

*The sensitivity coefficient is based on typical values for LEDs of this type.

Table 4-75. NIST uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Degrees of freedom	Correlated?
NIST standard spectral irradiance FEL lamp	0.00015 0.00021	B	Normal	1	0.00015 0.00021	∞	Yes
Instrument wavelength error	0.00025 0.00034	B	Rectangular	1	0.00025 0.00034	∞	Yes
Instrument bandpass (nm)	3	B	Rectangular	0.00003	0.00009 0.00009	∞	Yes
Instrument residual signal-level nonlinearity	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
Instrument residual spectral stray light	0.00005 0.00005	B	Normal	1	0.00005 0.00005	∞	Yes
Instrument calibration against standard spectral irradiance FEL lamps	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
LED alignment: angle of LED's geometric axis	0.00020 0.00020	A	Normal	1	0.00020 0.00020	∞	No
LED alignment: position of LED's geometric axis	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED alignment: distance from the LED's front tip to the entrance aperture	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED current (%)	0.01	B	Normal	0.001	0.00001 0.00001	1	Yes
LED ambient temperature (°C)*	0.58	B	Rectangular	0.00020 0.00006	0.00012 0.00003	∞	Yes
LED repeatability and reproducibility	0.00020 0.00020	A	Normal	1	0.00020 0.00020	3	No
Combined standard uncertainty			Normal		0.00044 0.00050	67 122	

*The sensitivity coefficient is based on typical values for LEDs of this type.

Table 4-76. NIST uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Degrees of freedom	Correlated?
NIST standard spectral irradiance FEL lamp	0.00010 0.00010	B	Normal	1	0.00010 0.00010	∞	Yes
Instrument wavelength error	0.00021 0.00019	B	Rectangular	1	0.00021 0.00019	∞	Yes
Instrument bandpass (nm)	3	B	Rectangular	0.00003	0.00009 0.00009	∞	Yes
Instrument residual signal-level nonlinearity	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
Instrument residual spectral stray light	0.00040 0.00040	B	Normal	1	0.00040 0.00040	∞	Yes
Instrument calibration against standard spectral irradiance FEL lamps	0.00001 0.00001	B	Normal	1	0.00001 0.00001	∞	Yes
LED alignment: angle of LED's geometric axis	0.00002 0.00002	A	Normal	1	0.00002 0.00002	∞	No
LED alignment: position of LED's geometric axis	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED alignment: distance from the LED's front tip to the entrance aperture	0.00001 0.00001	A	Normal	1	0.00001 0.00001	∞	No
LED current (%)	0.01	B	Normal	0.001	0.00001 0.00001	1	Yes
LED ambient temperature (°C)*	0.58	B	Rectangular	0.00004	0.00002 0.00002	∞	Yes
LED repeatability and reproducibility	0.00005 0.00005	A	Normal	1	0.00005 0.00005	3	No
Combined standard uncertainty			Normal		0.00048 0.00047	2.5×10^4 2.3×10^4	

*The sensitivity coefficient is based on typical values for LEDs of this type.

Table 4-77. NIST uncertainty budget of junction voltage measurement (typical).

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Degrees of freedom	Correlated ?
Voltmeter calibration	0.002	B	normal	1	0.002	∞	Yes
Wire junction position dependence	0.001	B	rectangular	1	0.001	∞	Yes
LED current (%)	0.010	B	normal	0.1	0.001	1	Yes
LED voltage measurement repeatability and reproducibility	0.006	A	normal	1	0.006	1	No
LED ambient temperature (°C)*	0.58	B	rectangular	0.2	0.116	∞	Yes
Combined standard uncertainty (%)			Normal		0.12	1.9×10^5	

4.12.VNIIOFI

Not submitted.

4.13.MKEH**4.13.1. Measurement setup**

The measurements were made with a spectral irradiance comparator developed at MKEH for LED measurements. Integrating sphere, aperture, double grating monochromator, order cutting filters, shutter, Si and PMT detectors, current integrator ore lock-in current meter and a computer are the main parts of the comparator. The comparator is calibrated with working standard spectral irradiance lamps which are traceable to our spectral irradiance standard lamps calibrated at NIST.

The measurement where made in the 380-760 nm spectral range in 1nm steps. The results are given in nW. The color coordinates were calculated with the help of the CIE 1931 colour matching functions.

4.13.2. Mounting and alignment

We have used an adjustment system for LED-s capable for 3 axis translation, pitch and rotation. We have used a laser which was centred and perpendicular to the detector and tried to centre the LED and align it's axis to the laser. First we tried a camera as it was mentioned but we were not happy with the results. Therefore we tried to use a direct visual method for the alignment. We found it better. The statistical uncertainty of the alignment of the different LEDs was given in my uncertainty budget in % of measured cd.

4.13.3. Traceability

All measurements are traceable to MKEH spectral responsivity and spectral irradiance scale. The MKEH spectral irradiance scale is traceable to the NIST scale.

4.13.4. Measurement uncertainty

Tables in the following show detailed uncertainty budgets of the CIE1931 x-y chromaticity coordinate measurement for the LEDs used in this APMP LED comparison.

The uncertainty budget for color coordinates is strongly depending on the sample to be measured. Therefore we calculated the uncertainty for each sample individually. In our case the main source of errors is the wavelength uncertainty and for some samples the dark noise.

The uncertainty budget represents just the method how we calculate the uncertainty and give ranges for the different components for different sources including narrow band- and tungsten light sources as well. The uncertainty is for tungsten sources the smallest. The combined standard uncertainty which is given in the table stands for tungsten source. The combined standard uncertainty for the CCPR LED-s is very different and significantly larger.

Table 4-78. MKEH uncertainty budget of CIE1931 x-y chromaticity coordinate for all LEDs (R,G,B,W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
spectral irradiance calibration	1.5 %	B	rectangular	Sample dependent	0.0003 ~ 0.002 0.0001 ~ 0.002	∞	O
wavelength error	0.1 nm	B	rectangular	Sample dependent	0.00005 ~ 0.001 0.00005 ~	∞	O

					0.001		
linearity	0.05 %	B	rectangular	Sample dependent	0.00005 0.00005	∞	O
stray light	10^{-15} W ~ 10^{-13} W	B	rectangular	Sample dependent	0.00005 ~ 0.0014 0.00005 ~ 0.002	∞	O
dark noise	2E-15 W	B	rectangular	Sample dependent	0.00003 ~ 0.002 0.00001 ~ 0.003	∞	X
room temp. dependence	1 K	B	rectangular	Sample dependent	<0.00005 <0.00005	∞	X
light source repeatability	As measured	A	normal	Sample dependent	As calculated	?	X
geometry error		B	rectangular	Sample dependent	As calculated	∞	O
Combined standard uncertainty	--	--	normal	--	0.0004 ~ 0.0026 0.0002 ~ 0.0032	∞	--

Table 4-79 is the detailed uncertainty budget of the junction voltage measurement.

Table 4-79. MKEH uncertainty budget of junction voltage measurement (typical).

Uncertainty Component	Standard uncertainty (%)	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Calibration of voltmeter	0.001	B	normal	1	0.001	∞	O
Junction position dependence	0.001	B	rectangular	1	0.001	∞	X
Reproducibility	0.001	A	normal	1	0.001	5	X
Combined standard uncertainty (%)	--	--	normal	--	0.001	??	--

4.14.INM

4.14.1. Measurement setup

At INM-Ro the measurement set-up is shown in Fig. 4-42.

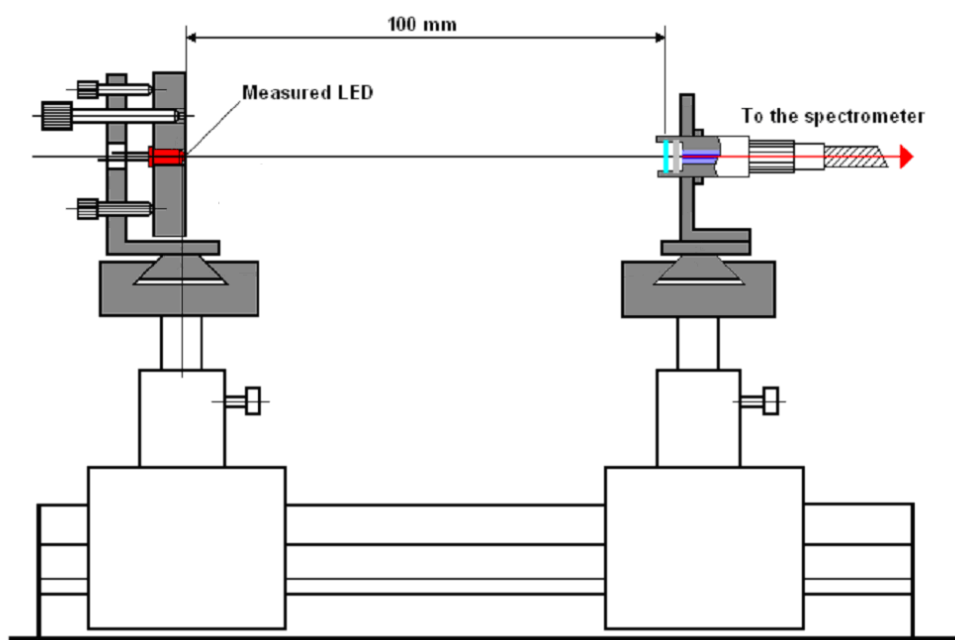


Fig. 4-42. Setup for emitted colours measurements in INM Romania.

For electrical measurements, a four wire technique as described in the comparison protocol was used in order to (almost) simultaneously measure the current fed into the measured LED and the junction voltage. The LED feeding current was generated by an adjustable voltage stabilised supply and a current measurement shunt across which the voltage was measured with a digital voltmeter. The LED junction voltage was measured with a similar digital voltmeter.

The measurement of the relative spectral density of the LED emitted flux was performed with a CCD spectrometer providing a (1 ± 0.1) nm bandwidth. The spectrometer input fibre head was provided with a diffusing + IR filter (Fig. 4-42).

4.14.2. Mounting and alignment

The measured LED was mounted in a similar manner as employed for average luminous intensity measurements except that no fine adjustment of the LED centring or alignment was performed for the emitted colour measurements. The LED and the input optical fibre were visually aligned.

4.14.3. Traceability

The spectrometer wavelength scale was calibrated against low pressure spectral Hg, Cd and He lamps traceable to the INM reference for length measurements (stabilised He-Ne

laser). It was found to be accurate within ± 0.3 nm for all wavelengths within the visible range.

The irradiance scale was calibrated against a irradiance spectral density lamp, traceable to the MIKES-TKK reference. The spectrometer photometric linearity was corrected and further checked against a set of spectral transmittance filters (neutral glass of NG type), traceable to the INM reference spectrophotometer.

All voltage measurements were traceable to the national references of Romania (group of stabilised Zener diodes of Fluke 732 B). The shunt resistance used to generate the feeding current was calibrated with traceability to the national references (group of electrical resistors).

The temperature was measured with a digital thermometer calibrated with traceability to the INM maintained SIT90 fixed points.

4.14.4. Measurement uncertainty

The expressions of the CIE1931 x-y chromaticity coordinates are:

$$x = C_1 \cdot C_2 \cdot \frac{X}{X + Y + Z}; \quad y = C_1 \cdot C_2 \cdot \frac{Y}{X + Y + Z}$$

where: C_1 is the feeding current factor; C_2 is the ambient temperature correction factor; and the CIE color matching functions:

$$\begin{aligned} X &= k \int_{380}^{830} S_{r,led}(\lambda) \cdot \bar{x}(\lambda) \cdot d\lambda; & Y &= k \int_{380}^{830} S_{r,led}(\lambda) \cdot \bar{y}(\lambda) \cdot d\lambda; \\ Z &= k \int_{380}^{830} S_{r,led}(\lambda) \cdot \bar{z}(\lambda) \cdot d\lambda; & k &= 100 / \int_{380}^{830} S_{r,led}(\lambda) \cdot \bar{y}(\lambda) \cdot d\lambda \end{aligned}$$

where: $S_{ph,rel}(\lambda)$ is the photometer relative spectral responsivity; $S_{led,r}(\lambda)$ is the LED relative spectral density and $V(\lambda)$ is the relative efficacy of the CIE standard observer.

Tables below are the detailed uncertainty budgets of the CIE1931 x-y chromaticity coordinate measurement for the LEDs used in this APMP LED comparison.

**Table 4-80. INM uncertainty budget of CIE1931 x-y chromaticity coordinate for red LEDs (R).
Upper values for x, lower values for y.**

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Feeding current factor C_1	0.0005 0.0005	B	normal	1	0.0005 0.0005	∞	O
Ambient temperature correction factor C_2	0.0005 0.0005	B	rectangular	1	0.0005 0.0005	∞	X
Color matching function ratios $X/(X+Y+Z)$ and $Y/(X+Y+Z)$	0.0008 0.0008	B	normal	1	0.0008 0.0008	∞	X
Repeatability	0.0004 0.0004	A	normal	1	0.0004 0.0004	∞	X
Combined standard uncertainty (%)	--	--	normal	--	0.0013	∞	--

Table 4-81. INM uncertainty budget of CIE1931 x-y chromaticity coordinate for green LEDs (G). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Feeding current factor C_1	0.0005 0.0005	B	normal	1	0.0005 0.0005	∞	O
Ambient temperature correction factor C_2	0.0005 0.0005	B	rectangular	1	0.0005 0.0005	∞	X
Color matching function ratios $X/(X+Y+Z)$ and $Y/(X+Y+Z)$	0.0008 0.0008	B	normal	1	0.0008 0.0008	∞	X
Repeatability	0.0004 0.0004	A	normal	1	0.0004 0.0004	∞	X
Combined standard uncertainty (%)	--	--	normal	--	0.0011	∞	--

Table 4-82. INM uncertainty budget of CIE1931 x-y chromaticity coordinate for blue LEDs (B). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Feeding current factor C_1	0.0005 0.0005	B	normal	1	0.0005 0.0005	∞	O
Ambient temp. factor C_2	0.0005 0.0005	B	rectangular	1	0.0005 0.0005	∞	X
Color matching function ratios $X/(X+Y+Z)$ and $Y/(X+Y+Z)$	0.0008 0.0008	B	normal	1	0.0008 0.0008	∞	X
Repeatability	0.0004 0.0004	A	normal	1	0.0004 0.0004	?	X

Combined standard uncertainty (%)	--	--	normal	--	0.0011	∞	--
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Table 4-83. INM uncertainty budget of CIE1931 x-y chromaticity coordinate for white LEDs (W). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Feeding current factor C_1	0.0005 0.0005	B	normal	1	0.0005 0.0005	∞	O
Ambient temp. factor C_2	0.0005 0.0005	B	rectangular	1	0.0005 0.0005	∞	X
Color matching function ratios $X/(X+Y+Z)$ and $Y/(X+Y+Z)$	0.0012 0.0012	B	normal	1	0.0012 0.0012	∞	X
Repeatability	0.0004 0.0004	A	normal	1	0.0004 0.0004	∞	X
Combined standard uncertainty (%)	--	--	normal	--	0.0013	∞	--

Table 4-84. INM uncertainty budget of CIE1931 x-y chromaticity coordinate for diffuser-type green LEDs (D). Upper values for x, lower values for y.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution	Deg. of freedom	Correlated?
Feeding current factor C_1	0.0005	B	normal	1	0.0005	∞	O
Ambient temperature correction factor C_2	0.0005	B	rectangular	1	0.0005	∞	X
Color matching function ratios $X/(X+Y+Z)$ and $Y/(X+Y+Z)$	0.0010	B	normal	1	0.0010	∞	X
Repeatability	0.0004	A	normal	1	0.0004	∞	X
Combined standard uncertainty (%)	--	--	normal	--	0.0011	∞	--

The junction voltage expression is:

$$V_j = C_1 \cdot C_2 \cdot \bar{V}_{read}$$

$\bar{V}_{read}$: the mean reading ; C_1 : temperature factor and C_2 : position factor

Table 4-85 is the detailed uncertainty budget of the junction voltage measurement.

Table 4-85. INM uncertainty budget of junction voltage measurement.

Uncertainty Component	Standard uncertainty	Type	Probability distribution	Sensitivity coefficient	Contribution (%)	Deg. of freedom	Correlated?
Mean reading $\bar{V}_{read}$	2E-5 V	B	normal	1	0.002	∞	O
Temperature factor C_1	0.0010	B	rectangular	1	0.10	∞	X
Position factor C_2	0.0005	B	rectangular	1	0.05	∞	X
Repeatability	0.0005	A	normal	1	0.05	∞	X
Combined standard uncertainty (%)	--	--	normal	--	0.12	∞	--

5. Reported Results of Participants

In this chapter, the results of the comparison S3c are presented, which are reported by each participant as the final version, i.e., after the verification in the pre-draft A process. We note that, throughout this report document, the uncertainty values with a symbol U indicate the expanded uncertainties for a confidence level of 95 % normally with a coverage factor of $k = 2$, while the values with a symbol u indicate the standard uncertainties.

5.1. KRISS

As the pilot laboratory of the comparison, KRISS measured each LED at most three times: the first measurement before sending the LEDs for the first round, the second after receiving the LEDs from the first round, and the third after receiving the LEDs from the second round. The final control measurement of the first round is also regarded as the initial control measurement of the second round. Note that the artefact sets #1, #4 and #8 are circulated only one round. The repeated measurements provide information on the stability of the artefact LEDs, which will be discussed in Section 6.2.

Table 5-1 summarizes the measurement results of KRISS of all the artefact LEDs. The uncertainty values are not explicitly shown in this table but referred to the budgets in Table 4-1~Table 4-6. The laboratory conditions are kept at a temperature of $(25 \pm 2) ^\circ\text{C}$ and a relative humidity of $(45 \pm 15) \%$. The burning time of each measurement was 20 minutes in average.

Table 5-1. Measurement results of KRISS.

set	LED	1. measurement			2. measurement			3. measurement		
		x	y	V_j (V)	x	y	V_j (V)	x	y	V_j (V)
#1	R-1	0.6996	0.2999	1.8847	0.6996	0.3000	1.8874			
	R-2	0.6992	0.3004	1.8880	0.6990	0.3005	1.8919			
	R-3	0.6988	0.3007	1.9213	0.6987	0.3009	1.9247			
	G-1	0.1635	0.7184	3.2968	0.1635	0.7184	3.3014			
	G-2	0.1648	0.7262	3.4375	0.1649	0.7261	3.4429			
	G-3	0.1453	0.7125	3.3150	0.1453	0.7125	3.3199			
	B-1	0.1291	0.0701	3.3763	0.1291	0.0702	3.3792			
	B-2	0.1265	0.0765	3.3770	0.1265	0.0765	3.3835			
	B-3	0.1235	0.0858	3.3470	0.1235	0.0858	3.3531			
	W-1	0.3349	0.3266	3.4448	0.3336	0.3248	3.4470			
	W-2	0.3214	0.3115	3.4647	0.3216	0.3119	3.4661			
	W-3	0.2978	0.2789	3.4190	0.2980	0.2793	3.4209			
	D-1	0.1676	0.7263	3.4742	0.1674	0.7277	3.4758			

	D-2	0.1727	0.7225	3.3116	0.1728	0.7226	3.3133			
#2	R-1	0.6989	0.3006	1.8941	0.6993	0.3002	1.8870	0.6993	0.3002	1.8870
	R-2	0.6985	0.3011	1.9040	0.6990	0.3006	1.8960	0.6990	0.3006	1.8960
	R-3	0.6976	0.3019	1.9088	0.6981	0.3014	1.9000	0.6981	0.3014	1.9000
	G-1	0.1555	0.7244	3.4762	0.1558	0.7246	3.4851	0.1559	0.7245	3.4818
	G-2	0.1673	0.7265	3.3955	0.1674	0.7266	3.4031	0.1677	0.7264	3.4005
	G-3	0.1624	0.7208	3.3057	0.1624	0.7208	3.3125	0.1625	0.7206	3.3105
	B-1	0.1261	0.0777	3.4554	0.1261	0.0778	3.4635	0.1261	0.0780	3.4588
	B-2	0.1230	0.0869	3.3735	0.1231	0.0865	3.3989	0.1229	0.0871	3.3804
	B-3	0.1289	0.0705	3.3547	0.1290	0.0706	3.3618	0.1289	0.0707	3.3600
	W-1	0.3290	0.3174	3.3040	0.3298	0.3183	3.3103	0.3296	0.3181	3.3068
	W-2	0.3070	0.2907	3.4232	0.3078	0.2918	3.4299	0.3075	0.2914	3.4242
	W-3	0.3074	0.2924	3.4513	0.3082	0.2934	3.4600	0.3084	0.2936	3.4590
	D-1	0.1526	0.7204	3.3998	0.1526	0.7206	3.4033	0.1532	0.7196	3.3968
	D-2	0.1586	0.7258	3.4883	0.1585	0.7262	3.4894	0.1594	0.7251	3.4845
#3	R-1	0.6984	0.3010	1.8955	0.6988	0.3007	1.8907	0.6988	0.3007	1.8899
	R-2	0.6981	0.3015	1.9004	0.6983	0.3012	1.8942	0.6984	0.3012	1.8930
	R-3	0.6978	0.3017	1.9047	0.6981	0.3014	1.8985	0.6981	0.3014	1.8975
	G-1	0.1507	0.7235	3.5276	0.1520	0.7231	3.5122	0.1520	0.7228	3.5091
	G-2	0.1694	0.7267	3.3919	0.1707	0.7261	3.3792	0.1708	0.7258	3.3758
	G-3	0.1432	0.7141	3.3535	0.1445	0.7142	3.3394	0.1445	0.7140	3.3374
	B-1	0.1251	0.0805	3.4480	0.1248	0.0817	3.4360	0.1248	0.0817	3.4333
	B-2	0.1245	0.0821	3.4350	0.1242	0.0833	3.4236	0.1241	0.0833	3.4206
	B-3	0.1303	0.0665	3.5336	0.1300	0.0673	3.5183	0.1300	0.0673	3.5159
	W-1	0.3273	0.3266	3.4552	0.3276	0.3273	3.4413	0.3278	0.3276	3.4403
	W-2	0.3232	0.3073	3.3560	0.3235	0.3080	3.3434	0.3237	0.3083	3.3427
	W-3	0.3324	0.3233	3.3232	0.3328	0.3240	3.3117	0.3331	0.3245	3.3102
	D-1	0.1705	0.7218	3.3275	0.1716	0.7211	3.3165	0.1710	0.7230	3.3170
	D-2	0.1694	0.7240	3.3305	0.1712	0.7214	3.3180	0.1707	0.7226	3.3179
#4	R-1	0.6987	0.3008	1.9012	0.6989	0.3007	1.8979			
	R-2	0.6984	0.3012	1.8971	0.6985	0.3011	1.8944			
	R-3	0.6981	0.3016	1.8985	0.6982	0.3014	1.8958			
	G-1	0.1491	0.7224	3.5240	0.1499	0.7222	3.5166			
	G-2	0.1697	0.7211	3.3085	0.1705	0.7209	3.3032			
	G-3	0.1501	0.7176	3.3699	0.1510	0.7174	3.3631			
	B-1	0.1216	0.0905	3.4319	0.1214	0.0914	3.4265			
	B-2	0.1280	0.0724	3.4746	0.1278	0.0731	3.4691			
	B-3	0.1252	0.0804	3.4114	0.1250	0.0812	3.4057			
	W-1	0.3250	0.3226	3.4499	0.3255	0.3236	3.4400			
	W-2	0.3224	0.3178	3.3503	0.3231	0.3190	3.3441			
	W-3	0.3125	0.3036	3.4570	0.3130	0.3045	3.4507			
	D-1	0.1674	0.7226	3.3118	0.1686	0.7211	3.3019			
	D-2	0.1681	0.7295	3.4139	0.1692	0.7275	3.4067			
#5	R-1	0.7002	0.2993	1.9192	0.7003	0.2993	1.9190	0.7002	0.2993	1.9194
	R-2	0.6999	0.2996	1.9232	0.7000	0.2996	1.9231	0.6999	0.2996	1.9239
	R-3	0.7000	0.2995	1.8859	0.7000	0.2996	1.8864	0.7000	0.2996	1.8866
	G-1	0.1565	0.7177	3.3123	0.1567	0.7177	3.3135	0.1567	0.7175	3.3138
	G-2	0.1628	0.7264	3.4479	0.1631	0.7265	3.4494	0.1631	0.7264	3.4511
	G-3	0.1688	0.7258	3.3807	0.1690	0.7259	3.3830	0.1689	0.7257	3.3842
	B-1	0.1270	0.0754	3.4131	0.1270	0.0755	3.4155	0.1270	0.0756	3.4140

	B-2	0.1214	0.0914	3.4153	0.1214	0.0915	3.4176	0.1214	0.0915	3.4157
	B-3	0.1245	0.0822	3.4281	0.1245	0.0823	3.4307	0.1246	0.0821	3.4333
	W-1	0.3281	0.3170	3.3227	0.3285	0.3177	3.3183	0.3285	0.3177	3.3147
	W-2	0.3117	0.3019	3.4493	0.3120	0.3025	3.4460	0.3118	0.3024	3.4412
	W-3	0.3120	0.3008	3.4553	0.3125	0.3015	3.4531	0.3126	0.3016	3.4545
	D-1	0.1579	0.7293	3.4806	0.1585	0.7262	3.4928	0.1582	0.7269	3.4951
	D-2	0.1551	0.7274	3.4911	0.1548	0.7269	3.5061	0.1550	0.7271	3.5028
#6	R-1	0.6985	0.3010	1.8993	0.6984	0.3012	1.9022	0.6984	0.3012	1.9012
	R-2	0.6990	0.3005	1.8857	0.6990	0.3006	1.8887	damaged		
	R-3	0.6985	0.3011	1.8955	0.6982	0.3013	1.8984	damaged		
	G-1	0.1701	0.7205	3.2991	0.1699	0.7206	3.3038	damaged		
	G-2	0.1685	0.7220	3.3015	0.1682	0.7222	3.3064	damaged		
	G-3	0.1633	0.7204	3.3217	0.1631	0.7206	3.3278	0.1631	0.7203	3.3252
	B-1	0.1205	0.0940	3.4192	0.1206	0.0938	3.4253	0.1206	0.0938	3.4225
	B-2	0.1282	0.0724	3.3771	0.1284	0.0722	3.3844	0.1284	0.0723	3.3816
	B-3	0.1264	0.0769	3.3829	0.1266	0.0767	3.3896	damaged		
	W-1	0.3271	0.3227	3.4078	0.3288	0.3249	3.4117	0.3288	0.3250	3.4110
	W-2	0.3152	0.3120	3.4050	0.3168	0.3141	3.4098	0.3169	0.3142	3.4089
	W-3	0.2985	0.2795	3.4214	0.2998	0.2812	3.4265	0.2998	0.2813	3.4246
	D-1	0.1483	0.7168	3.3563	0.1478	0.7170	3.3667	0.1483	0.7156	3.3673
	D-2	0.1619	0.7255	3.4500	0.1612	0.7267	3.4605	damaged		
#7	R-1	0.6994	0.3002	1.9222	0.6993	0.3002	1.9212	0.6995	0.3000	1.9174
	R-2	0.6993	0.3002	1.9038	0.6993	0.3003	1.9034	0.6995	0.3001	1.8995
	R-3	0.6992	0.3003	1.9202	0.6991	0.3004	1.9202	0.6993	0.3002	1.9163
	G-1	0.1673	0.7197	3.2993	0.1674	0.7197	3.2978	0.1678	0.7195	3.2908
	G-2	0.1696	0.7254	3.3643	0.1697	0.7253	3.3626	0.1700	0.7251	3.3543
	G-3	0.1673	0.7197	3.3044	0.1675	0.7196	3.3022	0.1678	0.7194	3.2950
	B-1	0.1252	0.0801	3.4658	0.1252	0.0803	3.4640	0.1249	0.0810	3.4548
	B-2	0.1267	0.0762	3.3992	0.1267	0.0764	3.3973	0.1266	0.0769	3.3887
	B-3	0.1238	0.0841	3.4294	0.1238	0.0843	3.4274	0.1237	0.0847	3.4184
	W-1	0.3349	0.3319	3.4763	0.3355	0.3328	3.4752	0.3353	0.3328	3.4598
	W-2	0.3250	0.3110	3.3647	0.3255	0.3117	3.3623	0.3253	0.3117	3.3514
	W-3	0.2971	0.2811	3.4170	0.2974	0.2816	3.4148	0.2972	0.2816	3.4047
	D-1	0.1663	0.7273	3.4567	0.1667	0.7280	3.4484	0.1671	0.7272	3.4424
	D-2	0.1528	0.7199	3.3809	0.1533	0.7199	3.3759	0.1533	0.7192	3.3749
#8	R-1	0.6985	0.3010	1.8899	0.6985	0.3010	1.8892			
	R-2	0.6982	0.3014	1.8940	0.6982	0.3013	1.8932			
	R-3	0.6988	0.3007	1.8990	0.6988	0.3007	1.8982			
	G-1	0.1469	0.7215	3.5387	0.1471	0.7214	3.5362			
	G-2	0.1672	0.7198	3.2958	0.1673	0.7198	3.2945			
	G-3	0.1661	0.7191	3.2980	0.1663	0.7192	3.2961			
	B-1	0.1233	0.0854	3.4510	0.1233	0.0857	3.4484			
	B-2	0.1278	0.0735	3.3671	0.1277	0.0738	3.3649			
	B-3	0.1276	0.0735	3.4690	0.1276	0.0737	3.4671			
	W-1	0.3163	0.3170	3.4306	0.3169	0.3178	3.4278			
	W-2	0.3307	0.3319	3.4308	0.3315	0.3329	3.4280			
	W-3	0.3263	0.3177	3.4671	0.3268	0.3184	3.4632			
	D-1	0.1705	0.7228	3.3192	0.1715	0.7214	3.3160			
	D-2	0.1650	0.7193	3.3067	0.1654	0.7192	3.3049			

5.2. MIKES

MIKES of Finland measured the artifact set #1 in its first round from 14 April 2008 to 20 April 2008. The laboratory conditions are reported as temperature of $(21.5 \pm 1.0) ^\circ\text{C}$ and relative humidity of $(31 \pm 5) \%$. Table 5-2 shows the reported results of MIKES.

Table 5-2. Measurement results of MIKES.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
#1	R-1	0.7016	0.2986	0.0024	0.0011	1.8939	0.0006	140
	R-2	0.7009	0.2988	0.0024	0.0011	1.8994	0.0006	80
	R-3	0.6997	0.2995	0.0024	0.0011	1.9310	0.0006	150
	G-1	0.1642	0.7237	0.0038	0.0015	3.3158	0.0009	90
	G-2	0.1686	0.7302	0.0038	0.0015	3.4543	0.0009	110
	G-3	0.1483	0.7188	0.0038	0.0015	3.3305	0.0009	110
	B-1	0.1274	0.0717	0.0014	0.0021	3.3939	0.0008	130
	B-2	0.1251	0.0790	0.0014	0.0021	3.3951	0.0008	80
	B-3	0.1211	0.0902	0.0014	0.0021	3.3715	0.0008	80
	W-1	0.3355	0.3253	0.0107	0.0162	3.4688	0.0010	140
	W-2	0.3248	0.3138	0.0107	0.0162	3.4873	0.0010	110
	W-3	0.3007	0.2815	0.0107	0.0162	3.4420	0.0010	160
	D-1	0.1721	0.7298	0.0130	0.0138	3.4920	0.0006	180
	D-2	0.1768	0.7245	0.0130	0.0138	3.3282	0.0006	180

5.3. CMS-ITRI

CMS-ITRI of Chinese Taipei measured the artifact set #2 in its first round from 13 May 2008 to 15 May 2008. The laboratory conditions are reported as temperature of $(23.0 \pm 1.5) ^\circ\text{C}$ and relative humidity of $(45 \pm 10) \%$. During the measurement at CMS-ITRI, however, all the three red LEDs were damaged so that the red LEDs of the set #2 had to be completely replaced for the second round. On the agreement of the other participants, CMS-ITRI repeated the measurement of the new red LEDs of the set #2 in Sept. ~ Oct. 2009. Table 5-3 shows the reported results of CMS-ITRI.

Table 5-3. Measurement results of CMS-ITRI.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
#2	R-1	0.6996	0.2998	0.0027	0.0044	1.900	0.001	60
	R-2	0.6991	0.3003	0.0027	0.0044	1.909	0.002	60
	R-3	0.6984	0.3010	0.0027	0.0044	1.914	0.002	60
	G-1	0.1605	0.7346	0.0036	0.0047	3.502	0.008	60
	G-2	0.1730	0.7339	0.0056	0.0068	3.419	0.008	60

	G-3	0.1698	0.7273	0.0031	0.0046	3.328	0.003	60
	B-1	0.1219	0.0840	0.0029	0.0047	3.479	0.003	60
	B-2	0.1192	0.0951	0.0038	0.0049	3.400	0.003	60
	B-3	0.1257	0.0765	0.0029	0.0046	3.378	0.003	60
	W-1	0.3313	0.3180	0.0047	0.0048	3.330	0.004	60
	W-2	0.3079	0.2923	0.0077	0.0056	3.452	0.003	60
	W-3	0.3075	0.2943	0.0037	0.0046	3.480	0.005	60
	D-1	0.160	0.728	0.018	0.017	3.411	0.005	60
	D-2	0.169	0.730	0.022	0.020	3.502	0.006	60

5.4. PTB

PTB of Germany measured the artifact set #3 in its first round from 16 June 2008 to 2 July 2008. The laboratory conditions are reported as temperature of $(25.0 \pm 0.7) ^\circ\text{C}$ and relative humidity of $(50 \pm 10) \%$. Table 5-4 shows the reported results of PTB.

Table 5-4. Measurement results of PTB.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (hour)
#3	R-1	0.7002	0.2994	0.0012	0.0009	1.8945	0.0012	9.8
	R-2	0.6999	0.2997	0.0012	0.0009	1.8976	0.0012	7.4
	R-3	0.6996	0.3000	0.0012	0.0009	1.9024	0.0012	7.1
	G-1	0.1544	0.7279	0.0020	0.0034	3.5230	0.0026	9.3
	G-2	0.1738	0.7294	0.0020	0.0034	3.3894	0.0025	4.6
	G-3	0.1470	0.7196	0.0020	0.0034	3.3503	0.0025	6.7
	B-1	0.1233	0.0840	0.0008	0.0013	3.4455	0.0017	9.6
	B-2	0.1226	0.0859	0.0008	0.0013	3.4338	0.0017	3.6
	B-3	0.1287	0.0692	0.0008	0.0013	3.5314	0.0017	6.8
	W-1	0.3276	0.3271	0.0017	0.0021	3.4509	0.0025	8.3
	W-2	0.3228	0.3065	0.0017	0.0021	3.3525	0.0025	8.3
	W-3	0.3323	0.3227	0.0017	0.0021	3.3217	0.0024	6.6
	D-1	0.1749	0.7243	0.0018	0.0030	3.3177	0.0017	1.6
	D-2	0.1744	0.7238	0.0018	0.0030	3.3182	0.0017	4.9

5.5. NMIJ

NMIJ of Japan measured the artifact set #4 in its first round from 15 April 2008 to 22 June 2008. The laboratory conditions are reported as temperature of $(23 \pm 2) ^\circ\text{C}$ and relative humidity of $(50 \pm 30) \%$. Table 5-5 shows the reported results of NMIJ.

Table 5-5. Measurement results of NMIJ.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
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#4	R-1	0.7003	0.2994	0.0008	0.0006	1.9037	0.0007	84
	R-2	0.6999	0.2999	0.0008	0.0006	1.9000	0.0007	78
	R-3	0.6996	0.3002	0.0008	0.0006	1.9014	0.0007	87
	G-1	0.1518	0.7279	0.0018	0.0026	3.5288	0.0010	78
	G-2	0.1726	0.7248	0.0018	0.0026	3.3114	0.0008	79
	G-3	0.1528	0.7229	0.0018	0.0026	3.3731	0.0008	58
	B-1	0.1201	0.0945	0.0006	0.0014	3.4351	0.0010	81
	B-2	0.1267	0.0755	0.0006	0.0014	3.4791	0.0006	78
	B-3	0.1238	0.0839	0.0006	0.0014	3.4150	0.0007	77
	W-1	0.3220	0.3200	0.0014	0.0018	3.4493	0.0009	84
	W-2	0.3197	0.3152	0.0014	0.0018	3.3546	0.0011	77
	W-3	0.3095	0.3009	0.0014	0.0018	3.4612	0.0009	83
	D-1	0.1730	0.7205	0.0016	0.0024	3.3057	0.0019	100
	D-2	0.1734	0.7276	0.0016	0.0024	3.4093	0.0019	89

5.6. CENAM

CENAM of Mexico measured the artifact set #5 in its first round from 17 July 2008 to 21 July 2008. The laboratory conditions are reported as temperature of (22.7 ± 2.2) °C and relative humidity of (47.5 ± 8.0) %. Table 5-6 shows the reported results of CENAM.

Table 5-6. Measurement results of CENAM.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
#5	R-1	0.5958	0.3073	0.0113	0.0014	1.9262	0.0010	56
	R-2	0.5948	0.3076	0.0095	0.0012	1.9305	0.0008	48
	R-3	0.5936	0.3068	0.0184	0.0020	1.8920	0.0006	45
	G-1	0.1944	0.6299	0.0020	0.0057	3.3297	0.0013	47
	G-2	0.1902	0.6674	0.0024	0.0065	3.4726	0.0020	51
	G-3	0.1919	0.6790	0.0024	0.0075	3.4040	0.0014	46
	B-1	0.1371	0.0795	0.0024	0.0027	3.4352	0.0014	48
	B-2	0.1349	0.0944	0.0030	0.0032	3.4375	0.0012	47
	B-3	0.1366	0.0863	0.0026	0.0031	3.4510	0.0013	52
	W-1	0.3334	0.3052	0.0009	0.0009	3.3372	0.0013	59
	W-2	0.3188	0.2926	0.0008	0.0009	3.4671	0.0011	47
	W-3	0.3191	0.2916	0.0008	0.0008	3.4731	0.0018	45
	D-1	0.2123	0.5857	0.0049	0.0143	3.5093	0.0016	51
	D-2	0.2093	0.5883	0.0055	0.0161	3.5209	0.0013	54

5.7. LNE

LNE of France measured the artifact set #6 in its first round from 15 June 2008 to 13 July 2008. The laboratory conditions are reported as temperature of (22 ± 2) °C and relative humidity of (50 ± 10) %. Table 5-7 shows the reported results of LNE.

Table 5-7. Measurement results of LNE.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
#6	R-1	0.6996	0.3002	0.0070	0.0030	1.90925	0.00057	N.A.
	R-2	0.7002	0.2995	0.0070	0.0030	1.89535	0.00057	N.A.
	R-3	0.6982	0.3015	0.0070	0.0030	1.90543	0.00057	N.A.
	G-1	0.1716	0.7242	0.0042	0.0072	3.312086	0.00066	N.A.
	G-2	0.1697	0.7261	0.0041	0.0073	3.312843	0.00066	N.A.
	G-3	0.1647	0.7247	0.0040	0.0072	3.335526	0.00067	N.A.
	B-1	0.1193	0.0952	0.0015	0.0044	3.43531	0.00069	N.A.
	B-2	0.1272	0.0730	0.0015	0.0034	3.39327	0.00068	N.A.
	B-3	0.1254	0.0775	0.0015	0.0036	3.39927	0.00068	N.A.
	W-1	0.3284	0.3229	0.0054	0.0085	3.41940	0.00068	N.A.
	W-2	0.3166	0.3129	0.0052	0.0082	3.42046	0.00068	N.A.
	W-3	0.2993	0.2795	0.0050	0.0074	3.43496	0.00069	N.A.
	D-1	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
	D-2	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

5.8. METAS

METAS of Switzerland measured the artifact set #7 in its first round from 15 July 2008 to 18 July 2008. The laboratory conditions are reported as temperature of $(25.0 \pm 0.5) ^\circ\text{C}$ and relative humidity of $(41 \pm 5) \%$. Table 5-8 shows the reported results of METAS.

Table 5-8. Measurement results of METAS.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
#7	R-1	0.70100	0.29880	0.00022	0.00026	1.9337	0.0082	290
	R-2	0.70090	0.29891	0.00029	0.00021	1.9133	0.0082	101
	R-3	0.70080	0.29900	0.00025	0.00021	1.9329	0.0082	103
	G-1	0.17029	0.72449	0.00080	0.00046	3.3132	0.063	119
	G-2	0.17280	0.72980	0.00085	0.00066	3.3791	0.063	82
	G-3	0.17065	0.72400	0.00083	0.00060	3.3165	0.063	162
	B-1	0.12390	0.08410	0.00026	0.00072	3.4821	0.075	135
	B-2	0.12550	0.08020	0.00028	0.00068	3.4140	0.075	96
	B-3	0.12255	0.08855	0.00031	0.00077	3.4455	0.075	104
	W-1	0.33520	0.33185	0.00081	0.00085	3.4939	0.083	183
	W-2	0.32475	0.31030	0.00092	0.00089	3.3787	0.083	88
	W-3	0.29755	0.28160	0.00063	0.00093	3.4334	0.083	100
	D-1	0.1701	0.7309	0.0048	0.0039	3.4599	0.063	139
	D-2	0.1567	0.7236	0.0043	0.0072	3.4029	0.063	176

5.9. NMC-A*STAR

NMC-A*STAR of Singapore measured the artifact set #8 in its first round from 10 July

2008 to 28 August 2008. The laboratory conditions are reported as temperature of (23 ± 2) °C and relative humidity of (60 ± 10) %. Table 5-9 shows the reported results of NMC-A*STAR.

Table 5-9. Measurement results of NMC-A*STAR.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
#8	R-1	0.7006	0.2993	0.0005	0.0005	1.8921	0.0022	NIL*
	R-2	0.7002	0.2997	0.0005	0.0005	1.8957	0.0022	NIL*
	R-3	0.7009	0.2990	0.0005	0.0005	1.9003	0.0022	NIL*
	G-1	0.1458	0.7333	0.0017	0.0023	3.5356	0.0024	NIL*
	G-2	0.1662	0.7336	0.0017	0.0023	3.2954	0.0024	NIL*
	G-3	0.1652	0.7332	0.0017	0.0023	3.2957	0.0024	NIL*
	B-1	0.1210	0.0894	0.0006	0.0016	3.4489	0.0025	NIL*
	B-2	0.1254	0.0775	0.0006	0.0016	3.3652	0.0025	NIL*
	B-3	0.1253	0.0774	0.0006	0.0016	3.4672	0.0025	NIL*
	W-1	0.3158	0.3169	0.0011	0.0014	3.4293	0.0041	NIL*
	W-2	0.3303	0.3317	0.0011	0.0014	3.4291	0.0041	NIL*
	W-3	0.3257	0.3174	0.0011	0.0014	3.4633	0.0041	NIL*
	D-1	0.1696	0.7347	0.0021	0.0034	3.3133	0.0021	NIL*
	D-2	0.1656	0.7316	0.0021	0.0034	3.3017	0.0021	NIL*

* Colour information was obtained when the Averaged LED Intensity (S3a) was measured

5.10. NMIA¹⁴

NMIA of Australia measured the artifact set #2 in its second round from 9 January 2009 to 9 May 2009. However, as the red LEDs of this set is replaced in the previous round of CMS-ITRI, the three red LEDs are measured by NMIA as the first round. The laboratory conditions are reported as temperature of (21.0 ± 0.5) °C and relative humidity of (50 ± 10) %. Table 5-10 shows the reported results of NMIA.

Table 5-10. Measurement results of NMIA.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
#2	R-1	0.6906	0.2997	0.0021	0.0008	1.90209	0.00014	2350
	R-2	0.6903	0.3004	0.0018	0.0008	1.91198	0.00014	430
	R-3	0.6883	0.3015	0.0019	0.0008	1.91743	0.00014	75
	G-1	0.1540	0.7224	0.0008	0.0009	3.52445	0.00025	70
	G-2	0.1646	0.7251	0.0007	0.0025	3.43681	0.00025	75

¹⁴ The final version of the results of NMIA is received on 01 July 2010 after the review of uncertainty budgets in the pre-draft A process.

	G-3	0.1603	0.7190	0.0007	0.0010	3.34151	0.00025	1010
	B-1	0.1276	0.0744	0.0007	0.0007	3.49167	0.00025	310
	B-2	0.1242	0.0838	0.0007	0.0007	3.41229	0.00025	70
	B-3	0.1302	0.0677	0.0007	0.0007	3.38591	0.00025	105
	W-1	0.3235	0.3135	0.0007	0.0007	3.34000	0.00025	155
	W-2	0.3048	0.2888	0.0007	0.0007	3.46348	0.00025	70
	W-3	0.3021	0.2871	0.0007	0.0007	3.49266	0.00025	965
	D-1	0.1521	0.7226	0.0007	0.0007	3.43581	0.00025	75
	D-2	0.1579	0.7276	0.0007	0.0007	3.52608	0.00025	195

5.11. NIST

NIST of the USA measured the artifact set #3 in its second round from 7 April 2009 to 8 April 2009. The laboratory conditions are reported as temperature of 25 °C and relative humidity of 9 %. Table 5-11 shows the reported results of NIST.

Table 5-11. Measurement results of NIST.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
#3	R-1	0.7006	0.2993	0.0003	0.0003	1.888	0.005	28
	R-2	0.7002	0.2997	0.0003	0.0003	1.892	0.005	28
	R-3	0.7000	0.2999	0.0003	0.0003	1.896	0.005	28
	G-1	0.1547	0.7281	0.0010	0.0010	3.503	0.009	28
	G-2	0.1739	0.7298	0.0010	0.0010	3.373	0.008	78
	G-3	0.1470	0.7202	0.0010	0.0010	3.334	0.008	28
	B-1	0.1229	0.0846	0.0004	0.0006	3.430	0.008	40
	B-2	0.1222	0.0864	0.0004	0.0006	3.417	0.008	40
	B-3	0.1283	0.0695	0.0004	0.0006	3.512	0.009	40
	W-1	0.3284	0.3283	0.0009	0.0010	3.438	0.008	28
	W-2	0.3237	0.3077	0.0009	0.0010	3.337	0.008	28
	W-3	0.3331	0.3238	0.0009	0.0010	3.306	0.008	28
	D-1	0.1749	0.7249	0.0010	0.0010	3.311	0.008	65
	D-2	0.1746	0.7246	0.0010	0.0010	3.313	0.008	40

5.12. VNIIOFI

VNIIOFI of Russia measured the artifact set #5 in its second round from 17 November 2008 to 19 November 2008. The laboratory conditions are reported as temperature of (22.0 ± 0.5) °C and relative humidity of (60 ± 4) %. Table 5-12 shows the reported results of VNIIOFI.

Table 5-12. Measurement results of VNIIOFI.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning
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								time (min)
#5	R-1	0.7013	0.2981	0.0018	0.0017	1.9324	0.0012	54
	R-2	0.701	0.2985	0.0018	0.0017	1.9362	0.0005	51
	R-3	0.7011	0.2983	0.0017	0.0018	1.8973	0.0004	50
	G-1	0.1609	0.7242	0.0019	0.0018	3.3383	0.001	61
	G-2	0.1679	0.7321	0.002	0.0018	3.4819	0.0015	50
	G-3	0.1743	0.7313	0.0023	0.0018	3.4107	0.0011	54
	B-1	0.1244	0.0802	0.0018	0.0021	3.4413	0.001	51
	B-2	0.1186	0.0973	0.0018	0.0023	3.4435	0.001	53
	B-3	0.1217	0.0878	0.0018	0.002	3.458	0.0008	53
	W-1	0.3293	0.3188	0.0018	0.0018	3.3445	0.001	54
	W-2	0.3132	0.305	0.0018	0.0018	3.4758	0.0013	53
	W-3	0.3136	0.3037	0.0018	0.0017	3.4848	0.001	52
	D-1	0.1644	0.7294	0.0028	0.0019	3.515	0.0008	52
	D-2	0.1619	0.7277	0.0025	0.0018	3.5263	0.0013	54

5.13.MKEH

MKEH of Hungary measured the artifact set #6 in its second round from 21 October 2008 to 29 October 2008. The laboratory conditions are reported as temperature of $(22.4 \pm 1.0) ^\circ\text{C}$ and relative humidity of $(30 \pm 10) \%$. Table 5-13 shows the reported results of MKEH. Note that one LED (#5-G-2) is damaged during the measurement in MKEH.

Table 5-13. Measurement results of MKEH.

set	LED	x	y	U(x)	U(y)	V _j (V)	U(V _j) (V)	burning time (min)
#6	R-1	0.6995	0.3004	0.0020	0.0017	1.9096	0.0005	140
	R-2	0.6998	0.3001	0.0021	0.0018	1.8985	0.0005	140
	R-3	0.6993	0.3006	0.0021	0.0018	1.908	0.0005	140
	G-1	0.1764	0.7262	0.0019	0.0011	3.325	0.0025	250
	G-2	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
	G-3	0.1690	0.7255	0.0019	0.0012	3.346	0.0015	270
	B-1	0.1201	0.0992	0.0014	0.0018	3.439	0.0005	160
	B-2	0.1276	0.0765	0.0014	0.0017	3.3955	0.0005	70
	B-3	0.1261	0.0812	0.0014	0.0017	3.404	0.001	100
	W-1	0.3212	0.3213	0.0033	0.0022	3.426	0.002	180
	W-2	0.3095	0.3105	0.0034	0.0023	3.424	0.001	70
	W-3	0.2906	0.2747	0.0033	0.0023	3.440	0.001	70
	D-1	0.1535	0.7200	0.0046	0.0048	3.375	0.001	100
	D-2	0.1670	0.7300	0.0048	0.0060	3.470	0.001	90

5.14.INM

INM of Romania measured the artifact set #7 in its second round from 13 December

2008 to 16 December 2008. The laboratory conditions are reported as temperature of $(25.0 \pm 0.2) ^\circ\text{C}$ and relative humidity of $(30 \pm 5) \%$. Table 5-14 shows the reported results of INM.

Table 5-14. Measurement results of INM.

set	LED	x	y	$U(x)$	$U(y)$	V_j (V)	$U(V_j)$ (V)	burning time (min)
#7	R-1	0.7020	0.2979	0.0028	0.0028	1.926	0.006	5
	R-2	0.7010	0.2980	0.0028	0.0028	1.907	0.006	5
	R-3	0.7012	0.2979	0.0028	0.0028	1.925	0.006	5
	G-1	0.1675	0.7273	0.0022	0.0022	3.302	0.010	5
	G-2	0.1704	0.7319	0.0022	0.0022	3.367	0.010	5
	G-3	0.1684	0.7272	0.0022	0.0022	3.307	0.010	5
	B-1	0.1232	0.0832	0.0022	0.0022	3.468	0.010	5
	B-2	0.1249	0.0791	0.0022	0.0022	3.402	0.010	5
	B-3	0.1218	0.0875	0.0022	0.0022	3.435	0.010	5
	W-1	0.3278	0.3216	0.0026	0.0026	3.479	0.010	5
	W-2	0.3197	0.3020	0.0026	0.0026	3.368	0.010	5
	W-3	0.2913	0.2733	0.0026	0.0026	3.420	0.010	5
	D-1	0.1679	0.7334	0.0022	0.0022	3.451	0.010	5
	D-2	0.1550	0.7267	0.0022	0.0022	3.452	0.010	5

6. Pre-draft A Process

After the measurement process is completed, the preparation of the comparison report is conducted according to the CCPR Guidelines.¹⁵ The pre-draft A process consists of verification of reported results, review of uncertainty budgets, and review of relative data. In this chapter, we also describe the temperature-corrected results and the identification of outliers.

6.1. Verification of Reported Results

The verification of reported results started in November 2009 after most of the participants have submitted their results. The pilot sent to each participant the submitted result values and the technical report including the uncertainty budgets. The participant reviewed it to correct any error. After the participant confirmed the final version, no correction is applied in the results and in the technical reports of the participants.

6.2. Temperature Correction and Artifact Drift

After the results are finalized by the verification, the pilot applied the temperature correction based on the Eq. (3-1). By using the temperature sensitivity coefficients a_x and a_y of each LED and the measured junction voltages reported by the participants, all the results could be converted to the values expected at the same junction voltage, i.e., at the same reference condition with a temperature of T_0 . We took the initial control measurement of the pilot for each round as the reference condition for correction.

The tables below summarize the results before and after the temperature correction for each measurement round. The uncertainties of the temperature correction are also shown at the last column, which are estimated based on the goodness of fit of Eq. (3-1) to the seasoning data.

Table 6-1. Results of temperature correction for the round to MIKES.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{p2}	y_{p2}	x_L^*	y_L^*	x_{p2}^*	y_{p2}^*	$u(x)_{\text{fit}}$	$u(y)_{\text{fit}}$
#1	R-1	0.7016	0.2986	0.6996	0.3000	0.7019	0.2982	0.6997	0.2999	0.0003	0.0001
	R-2	0.7009	0.2988	0.6990	0.3005	0.7013	0.2984	0.6992	0.3004	0.0003	0.0001
	R-3	0.6997	0.2995	0.6987	0.3009	0.7001	0.2991	0.6988	0.3007	0.0006	0.0001
	G-1	0.1642	0.7237	0.1635	0.7184	0.1651	0.7233	0.1637	0.7183	0.0005	0.0005

¹⁵ CCPR Key Comparison Working Group, *Guidelines for CCPR Comparison Report Preparation*, Rev. 2 (Sept. 18, 2009), available at http://www.bipm.org/en/committees/cc/ccpr/publications_cc.html

	G-2	0.1686	0.7302	0.1649	0.7261	0.1694	0.7298	0.1651	0.7260	0.0014	0.0007
	G-3	0.1483	0.7188	0.1453	0.7125	0.1489	0.7187	0.1455	0.7125	0.0010	0.0005
	B-1	0.1274	0.0717	0.1291	0.0702	0.1271	0.0725	0.1290	0.0703	0.0001	0.0002
	B-2	0.1251	0.0790	0.1265	0.0765	0.1249	0.0797	0.1264	0.0767	0.0001	0.0001
	B-3	0.1211	0.0902	0.1235	0.0858	0.1209	0.0910	0.1235	0.0860	0.0002	0.0001
	W-1	0.3355	0.3253	0.3336	0.3248	0.3346	0.3245	0.3335	0.3247	0.0007	0.0009
	W-2	0.3248	0.3138	0.3216	0.3119	0.3239	0.3130	0.3216	0.3118	0.0006	0.0006
	W-3	0.3007	0.2815	0.2980	0.2793	0.2997	0.2807	0.2979	0.2793	0.0008	0.0008
	D-1	0.1721	0.7298	0.1674	0.7277	0.1728	0.7291	0.1675	0.7277	0.0006	0.0020
	D-2	0.1768	0.7245	0.1728	0.7226	0.1778	0.7240	0.1729	0.7225	0.0003	0.0005

Table 6-2. Results of temperature correction for the round to CMS-ITRI.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{\text{fit}}$	$u(y)_{\text{fit}}$
#2	R-1	0.6996	0.2998	0.6989	0.3006	0.7001	0.2993	0.6992	0.3003	0.0003	0.0001
	R-2	0.6991	0.3003	0.6985	0.3011	0.6996	0.2998	0.6988	0.3007	0.0004	0.0002
	R-3	0.6984	0.3010	0.6976	0.3019	0.6990	0.3004	0.6980	0.3015	0.0003	0.0002
	G-1	0.1605	0.7346	0.1558	0.7246	0.1615	0.7339	0.1561	0.7244	0.0018	0.0019
	G-2	0.1730	0.7339	0.1674	0.7266	0.1740	0.7332	0.1678	0.7263	0.0003	0.0005
	G-3	0.1698	0.7273	0.1624	0.7208	0.1709	0.7270	0.1627	0.7207	0.0010	0.0003
	B-1	0.1219	0.0840	0.1261	0.0778	0.1216	0.0850	0.1260	0.0782	0.0001	0.0001
	B-2	0.1192	0.0951	0.1231	0.0865	0.1190	0.0961	0.1229	0.0874	0.0002	0.0004
	B-3	0.1257	0.0765	0.1290	0.0706	0.1254	0.0775	0.1289	0.0710	0.0001	0.0002
	W-1	0.3313	0.3180	0.3298	0.3183	0.3302	0.3170	0.3295	0.3181	0.0015	0.0015
	W-2	0.3079	0.2923	0.3078	0.2918	0.3066	0.2912	0.3075	0.2916	0.0018	0.0018
	W-3	0.3075	0.2943	0.3082	0.2934	0.3062	0.2933	0.3079	0.2931	0.0022	0.0022
	D-1	0.160	0.728	0.1526	0.7206	0.1605	0.7278	0.1528	0.7206	0.0012	0.0007
	D-2	0.169	0.730	0.1585	0.7262	0.1695	0.7297	0.1586	0.7262	0.0006	0.0010

Table 6-3. Results of temperature correction for the round to PTB.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{\text{fit}}$	$u(y)_{\text{fit}}$
#3	R-1	0.7002	0.2994	0.6988	0.3007	0.7002	0.2994	0.6986	0.3009	0.0003	0.0002
	R-2	0.6999	0.2997	0.6983	0.3012	0.6997	0.2999	0.6981	0.3015	0.0003	0.0001
	R-3	0.6996	0.3000	0.6981	0.3014	0.6995	0.3002	0.6978	0.3017	0.0005	0.0001
	G-1	0.1544	0.7279	0.1520	0.7231	0.1541	0.7282	0.1515	0.7235	0.0020	0.0023
	G-2	0.1738	0.7294	0.1707	0.7261	0.1732	0.7299	0.1701	0.7265	0.0004	0.0003
	G-3	0.1470	0.7196	0.1445	0.7142	0.1464	0.7198	0.1439	0.7145	0.0024	0.0004
	B-1	0.1233	0.0840	0.1248	0.0817	0.1234	0.0837	0.1249	0.0811	0.0001	0.0001
	B-2	0.1226	0.0859	0.1242	0.0833	0.1227	0.0855	0.1243	0.0827	0.0001	0.0001
	B-3	0.1287	0.0692	0.1300	0.0673	0.1288	0.0689	0.1302	0.0670	0.0001	0.0003
	W-1	0.3276	0.3271	0.3276	0.3273	0.3282	0.3272	0.3282	0.3277	0.0010	0.0008
	W-2	0.3228	0.3065	0.3235	0.3080	0.3234	0.3067	0.3240	0.3084	0.0011	0.0008
	W-3	0.3323	0.3227	0.3328	0.3240	0.3327	0.3227	0.3333	0.3244	0.0011	0.0009
	D-1	0.1749	0.7243	0.1716	0.7211	0.1742	0.7247	0.1709	0.7214	0.0003	0.0006

	D-2	0.1744	0.7238	0.1712	0.7214	0.1741	0.7241	0.1706	0.7216	0.0003	0.0005
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Table 6-4. Results of temperature correction for the round to NMIJ.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{\text{fit}}$	$u(y)_{\text{fit}}$
#4	R-1	0.7003	0.2994	0.6989	0.3007	0.7004	0.2993	0.6988	0.3008	0.0006	0.0002
	R-2	0.6999	0.2999	0.6985	0.3011	0.7000	0.2998	0.6984	0.3012	0.0007	0.0002
	R-3	0.6996	0.3002	0.6982	0.3014	0.6997	0.3001	0.6980	0.3015	0.0003	0.0001
	G-1	0.1518	0.7279	0.1499	0.7222	0.1520	0.7278	0.1497	0.7224	0.0021	0.0010
	G-2	0.1726	0.7248	0.1705	0.7209	0.1728	0.7247	0.1702	0.7210	0.0011	0.0004
	G-3	0.1528	0.7229	0.1510	0.7174	0.1529	0.7228	0.1507	0.7176	0.0019	0.0004
	B-1	0.1201	0.0945	0.1214	0.0914	0.1201	0.0947	0.1215	0.0911	0.0001	0.0001
	B-2	0.1267	0.0755	0.1278	0.0731	0.1266	0.0757	0.1279	0.0729	0.0002	0.0006
	B-3	0.1238	0.0839	0.1250	0.0812	0.1237	0.0841	0.1251	0.0809	0.0001	0.0001
	W-1	0.3220	0.3200	0.3255	0.3236	0.3220	0.3200	0.3260	0.3240	0.0020	0.0018
	W-2	0.3197	0.3152	0.3231	0.3190	0.3195	0.3151	0.3234	0.3192	0.0021	0.0018
	W-3	0.3095	0.3009	0.3130	0.3045	0.3093	0.3007	0.3133	0.3047	0.0019	0.0017
	D-1	0.1730	0.7205	0.1686	0.7211	0.1727	0.7205	0.1682	0.7211	0.0009	0.0017
	D-2	0.1734	0.7276	0.1692	0.7275	0.1732	0.7277	0.1689	0.7277	0.0003	0.0014

Table 6-5. Results of temperature correction for the round to CENAM.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{\text{fit}}$	$u(y)_{\text{fit}}$
#5	R-1	0.5958	0.3073	0.7003	0.2993	0.5960	0.3071	0.7003	0.2993	0.0006	0.0003
	R-2	0.5948	0.3076	0.7000	0.2996	0.5950	0.3073	0.7000	0.2996	0.0004	0.0002
	R-3	0.5936	0.3068	0.7000	0.2996	0.5938	0.3066	0.7000	0.2995	0.0003	0.0002
	G-1	0.1944	0.6299	0.1567	0.7177	0.1952	0.6296	0.1567	0.7177	0.0008	0.0006
	G-2	0.1902	0.6674	0.1631	0.7265	0.1912	0.6666	0.1631	0.7265	0.0005	0.0008
	G-3	0.1919	0.6790	0.1690	0.7259	0.1930	0.6781	0.1691	0.7258	0.0002	0.0003
	B-1	0.1371	0.0795	0.1270	0.0755	0.1367	0.0805	0.1269	0.0756	0.0001	0.0003
	B-2	0.1349	0.0944	0.1214	0.0915	0.1346	0.0956	0.1214	0.0916	0.0001	0.0002
	B-3	0.1366	0.0863	0.1245	0.0823	0.1363	0.0874	0.1245	0.0824	0.0001	0.0002
	W-1	0.3334	0.3052	0.3285	0.3177	0.3327	0.3045	0.3288	0.3179	0.0006	0.0009
	W-2	0.3188	0.2926	0.3120	0.3025	0.3179	0.2917	0.3122	0.3027	0.0009	0.0007
	W-3	0.3191	0.2916	0.3125	0.3015	0.3181	0.2907	0.3126	0.3016	0.0009	0.0007
	D-1	0.2123	0.5857	0.1585	0.7262	0.2135	0.5849	0.1590	0.7258	0.0009	0.0013
	D-2	0.2093	0.5883	0.1548	0.7269	0.2105	0.5875	0.1554	0.7265	0.0011	0.0030

Table 6-6. Results of temperature correction for the round to LNE.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{\text{fit}}$	$u(y)_{\text{fit}}$
#6	R-1	0.6996	0.3002	0.6984	0.3012	0.6999	0.2997	0.6985	0.3010	0.0003	0.0003

	R-2	0.7002	0.2995	0.6990	0.3006	0.7006	0.2991	0.6991	0.3005	0.0004	0.0001
	R-3	0.6982	0.3015	0.6982	0.3013	0.6987	0.3011	0.6984	0.3012	0.0003	0.0003
	G-1	0.1716	0.7242	0.1699	0.7206	0.1723	0.7239	0.1701	0.7205	0.0003	0.0005
	G-2	0.1697	0.7261	0.1682	0.7222	0.1703	0.7258	0.1684	0.7221	0.0003	0.0004
	G-3	0.1647	0.7247	0.1631	0.7206	0.1652	0.7243	0.1633	0.7204	0.0004	0.0004
	B-1	0.1193	0.0952	0.1206	0.0938	0.1191	0.0961	0.1205	0.0941	0.0001	0.0002
	B-2	0.1272	0.0730	0.1284	0.0722	0.1269	0.0738	0.1282	0.0725	0.0001	0.0001
	B-3	0.1254	0.0775	0.1266	0.0767	0.1252	0.0783	0.1265	0.0770	0.0001	0.0001
	W-1	0.3284	0.3229	0.3288	0.3249	0.3277	0.3224	0.3286	0.3247	0.0016	0.0017
	W-2	0.3166	0.3129	0.3168	0.3141	0.3157	0.3122	0.3166	0.3139	0.0016	0.0017
	W-3	0.2993	0.2795	0.2998	0.2812	0.2985	0.2788	0.2995	0.2810	0.0015	0.0017
	D-1	N.A.	N.A.	0.1478	0.7170	N.A.	N.A.	0.1483	0.7168	0.0010	0.0008
	D-2	N.A.	N.A.	0.1612	0.7267	N.A.	N.A.	0.1616	0.7264	0.0005	0.0012

Table 6-7. Results of temperature correction for the round to METAS.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{\text{fit}}$	$u(y)_{\text{fit}}$
#7	R-1	0.70100	0.29880	0.6993	0.3002	0.7013	0.2983	0.6993	0.3002	0.0002	0.0001
	R-2	0.70090	0.29891	0.6993	0.3003	0.7014	0.2985	0.6993	0.3003	0.0003	0.0001
	R-3	0.70080	0.29900	0.6991	0.3004	0.7012	0.2986	0.6991	0.3004	0.0006	0.0001
	G-1	0.17029	0.72449	0.1674	0.7197	0.1710	0.7242	0.1673	0.7197	0.0006	0.0005
	G-2	0.17280	0.72980	0.1697	0.7253	0.1734	0.7295	0.1696	0.7254	0.0006	0.0004
	G-3	0.17065	0.72400	0.1675	0.7196	0.1712	0.7238	0.1674	0.7197	0.0006	0.0003
	B-1	0.12390	0.08410	0.1252	0.0803	0.1237	0.0848	0.1252	0.0802	0.0002	0.0004
	B-2	0.12550	0.08020	0.1267	0.0764	0.1253	0.0809	0.1267	0.0763	0.0001	0.0002
	B-3	0.12255	0.08855	0.1238	0.0843	0.1224	0.0891	0.1238	0.0842	0.0001	0.0003
	W-1	0.33520	0.33185	0.3355	0.3328	0.3345	0.3312	0.3356	0.3329	0.0025	0.0029
	W-2	0.32475	0.31030	0.3255	0.3117	0.3242	0.3098	0.3256	0.3118	0.0020	0.0020
	W-3	0.29755	0.28160	0.2974	0.2816	0.2968	0.2811	0.2975	0.2817	0.0022	0.0025
	D-1	0.1701	0.7309	0.1667	0.7280	0.1702	0.7308	0.1663	0.7282	0.0003	0.0018
	D-2	0.1567	0.7236	0.1533	0.7199	0.1575	0.7233	0.1531	0.7199	0.0003	0.0006

Table 6-8. Results of temperature correction for the round to NMC-A*STAR.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{\text{fit}}$	$u(y)_{\text{fit}}$
#8	R-1	0.7006	0.2993	0.6985	0.3010	0.7007	0.2992	0.6985	0.3010	0.0005	0.0002
	R-2	0.7002	0.2997	0.6982	0.3013	0.7003	0.2996	0.6982	0.3014	0.0003	0.0002
	R-3	0.7009	0.2990	0.6988	0.3007	0.7010	0.2989	0.6987	0.3007	0.0002	0.0001
	G-1	0.1458	0.7333	0.1471	0.7214	0.1457	0.7334	0.1470	0.7215	0.0017	0.0018
	G-2	0.1662	0.7336	0.1673	0.7198	0.1662	0.7336	0.1672	0.7198	0.0003	0.0004
	G-3	0.1652	0.7332	0.1663	0.7192	0.1651	0.7333	0.1662	0.7192	0.0006	0.0003
	B-1	0.1210	0.0894	0.1233	0.0857	0.1210	0.0893	0.1233	0.0856	0.0001	0.0001
	B-2	0.1254	0.0775	0.1277	0.0738	0.1254	0.0774	0.1278	0.0737	0.0001	0.0002
	B-3	0.1253	0.0774	0.1276	0.0737	0.1253	0.0773	0.1276	0.0737	0.0002	0.0006
	W-1	0.3158	0.3169	0.3169	0.3178	0.3159	0.3169	0.3170	0.3179	0.0008	0.0009

	W-2	0.3303	0.3317	0.3315	0.3329	0.3304	0.3317	0.3316	0.3329	0.0007	0.0010
	W-3	0.3257	0.3174	0.3268	0.3184	0.3259	0.3175	0.3270	0.3186	0.0014	0.0016
	D-1	0.1696	0.7347	0.1715	0.7214	0.1693	0.7348	0.1713	0.7215	0.0003	0.0006
	D-2	0.1656	0.7316	0.1654	0.7192	0.1653	0.7317	0.1653	0.7193	0.0003	0.0006

Table 6-9. Results of temperature correction for the round to NMIA.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{fit}$	$u(y)_{fit}$
#2	R-1	0.6906	0.2997	0.6993	0.3002	0.6912	0.2992	0.6993	0.3003	0.0003	0.0001
	R-2	0.6903	0.3004	0.6990	0.3006	0.6909	0.2998	0.6989	0.3007	0.0004	0.0002
	R-3	0.6883	0.3015	0.6981	0.3014	0.6890	0.3008	0.6981	0.3015	0.0003	0.0002
	G-1	0.1540	0.7224	0.1559	0.7245	0.1555	0.7213	0.1558	0.7246	0.0018	0.0019
	G-2	0.1646	0.7251	0.1677	0.7264	0.1660	0.7241	0.1675	0.7265	0.0003	0.0005
	G-3	0.1603	0.7190	0.1625	0.7206	0.1618	0.7185	0.1624	0.7206	0.0010	0.0003
	B-1	0.1276	0.0744	0.1261	0.0780	0.1273	0.0756	0.1261	0.0778	0.0001	0.0001
	B-2	0.1242	0.0838	0.1229	0.0871	0.1241	0.0843	0.1231	0.0864	0.0002	0.0004
	B-3	0.1302	0.0677	0.1289	0.0707	0.1298	0.0688	0.1289	0.0706	0.0001	0.0002
	W-1	0.3235	0.3135	0.3296	0.3181	0.3222	0.3124	0.3297	0.3182	0.0015	0.0015
	W-2	0.3048	0.2888	0.3075	0.2914	0.3033	0.2876	0.3078	0.2916	0.0018	0.0018
	W-3	0.3021	0.2871	0.3084	0.2936	0.3006	0.2859	0.3084	0.2936	0.0022	0.0022
	D-1	0.1521	0.7226	0.1532	0.7196	0.1535	0.7219	0.1529	0.7198	0.0012	0.0007
	D-2	0.1579	0.7276	0.1594	0.7251	0.1593	0.7267	0.1592	0.7252	0.0006	0.0010

Table 6-10. Results of temperature correction for the round to NIST.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{fit}$	$u(y)_{fit}$
#3	R-1	0.7006	0.2993	0.6988	0.3007	0.7005	0.2994	0.6988	0.3007	0.0003	0.0002
	R-2	0.7002	0.2997	0.6984	0.3012	0.7001	0.2998	0.6984	0.3012	0.0003	0.0001
	R-3	0.7000	0.2999	0.6981	0.3014	0.6999	0.3000	0.6981	0.3014	0.0005	0.0001
	G-1	0.1547	0.7281	0.1520	0.7228	0.1544	0.7284	0.1519	0.7229	0.0020	0.0023
	G-2	0.1739	0.7298	0.1708	0.7258	0.1736	0.7300	0.1706	0.7260	0.0004	0.0003
	G-3	0.1470	0.7202	0.1445	0.7140	0.1467	0.7203	0.1444	0.7140	0.0024	0.0004
	B-1	0.1229	0.0846	0.1248	0.0817	0.1230	0.0843	0.1248	0.0816	0.0001	0.0001
	B-2	0.1222	0.0864	0.1241	0.0833	0.1223	0.0861	0.1242	0.0832	0.0001	0.0001
	B-3	0.1283	0.0695	0.1300	0.0673	0.1283	0.0693	0.1301	0.0673	0.0001	0.0003
	W-1	0.3284	0.3283	0.3278	0.3276	0.3285	0.3284	0.3279	0.3277	0.0010	0.0008
	W-2	0.3237	0.3077	0.3237	0.3083	0.3240	0.3079	0.3238	0.3083	0.0011	0.0008
	W-3	0.3331	0.3238	0.3331	0.3245	0.3333	0.3240	0.3332	0.3245	0.0011	0.0009
	D-1	0.1749	0.7249	0.1710	0.7230	0.1746	0.7250	0.1710	0.7230	0.0003	0.0006
	D-2	0.1746	0.7246	0.1707	0.7226	0.1744	0.7247	0.1707	0.7226	0.0003	0.0005

Table 6-11. Results of temperature correction for the round to VNIIOFI.

set	LED	participant	2. meas. of pilot	temperature corrected	uncertainty of
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										correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{fit}$	$u(y)_{fit}$
#5	R-1	0.7013	0.2981	0.7002	0.2993	0.7017	0.2976	0.7002	0.2993	0.0006	0.0003
	R-2	0.7010	0.2985	0.6999	0.2996	0.7013	0.2979	0.7000	0.2996	0.0004	0.0002
	R-3	0.7011	0.2983	0.7000	0.2996	0.7015	0.2978	0.7000	0.2996	0.0003	0.0002
	G-1	0.1609	0.7242	0.1567	0.7175	0.1620	0.7237	0.1567	0.7175	0.0008	0.0006
	G-2	0.1679	0.7321	0.1631	0.7264	0.1691	0.7310	0.1631	0.7264	0.0005	0.0008
	G-3	0.1743	0.7313	0.1689	0.7257	0.1755	0.7302	0.1690	0.7257	0.0002	0.0003
	B-1	0.1244	0.0802	0.1270	0.0756	0.1240	0.0814	0.1270	0.0755	0.0001	0.0003
	B-2	0.1186	0.0973	0.1214	0.0915	0.1182	0.0987	0.1215	0.0914	0.0001	0.0002
	B-3	0.1217	0.0878	0.1246	0.0821	0.1213	0.0891	0.1245	0.0822	0.0001	0.0002
	W-1	0.3293	0.3188	0.3285	0.3177	0.3279	0.3176	0.3287	0.3179	0.0006	0.0009
	W-2	0.3132	0.3050	0.3118	0.3024	0.3116	0.3036	0.3121	0.3026	0.0009	0.0007
	W-3	0.3136	0.3037	0.3126	0.3016	0.3118	0.3021	0.3125	0.3015	0.0009	0.0007
	D-1	0.1644	0.7294	0.1582	0.7269	0.1653	0.7288	0.1583	0.7269	0.0009	0.0013
	D-2	0.1619	0.7277	0.1550	0.7271	0.1627	0.7272	0.1548	0.7272	0.0011	0.0030

Table 6-12. Results of temperature correction for the round to MKEH.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{fit}$	$u(y)_{fit}$
#6	R-1	0.6995	0.3004	0.6984	0.3012	0.6998	0.3001	0.6984	0.3012	0.0003	0.0003
	R-2	0.6998	0.3001	N.A.	N.A.	0.7002	0.2997	N.A.	N.A.	0.0004	0.0001
	R-3	0.6993	0.3006	N.A.	N.A.	0.6998	0.3002	N.A.	N.A.	0.0003	0.0003
	G-1	0.1764	0.7262	N.A.	N.A.	0.1775	0.7257	N.A.	N.A.	0.0003	0.0005
	G-2	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0.0003	0.0004
	G-3	0.1690	0.7255	0.1631	0.7203	0.1697	0.7250	0.1630	0.7204	0.0004	0.0004
	B-1	0.1201	0.0992	0.1206	0.0938	0.1199	0.0999	0.1207	0.0937	0.0001	0.0002
	B-2	0.1276	0.0765	0.1284	0.0723	0.1274	0.0770	0.1284	0.0721	0.0001	0.0001
	B-3	0.1261	0.0812	N.A.	N.A.	0.1259	0.0819	N.A.	N.A.	0.0001	0.0001
	W-1	0.3212	0.3213	0.3288	0.3250	0.3204	0.3206	0.3288	0.3250	0.0016	0.0017
	W-2	0.3095	0.3105	0.3169	0.3142	0.3087	0.3098	0.3169	0.3142	0.0016	0.0017
	W-3	0.2906	0.2747	0.2998	0.2813	0.2898	0.2740	0.2999	0.2814	0.0015	0.0017
	D-1	0.1535	0.7200	0.1483	0.7156	0.1539	0.7198	0.1483	0.7156	0.0010	0.0008
	D-2	0.1670	0.7300	N.A.	N.A.	0.1673	0.7297	N.A.	N.A.	0.0005	0.0012

Table 6-13. Results of temperature correction for the round to INM.

set	LED	participant		2. meas. of pilot		temperature corrected				uncertainty of correction	
		x_L	y_L	x_{P2}	y_{P2}	x_L^*	y_L^*	x_{P2}^*	y_{P2}^*	$u(x)_{fit}$	$u(y)_{fit}$
#7	R-1	0.7020	0.2979	0.6995	0.3000	0.7021	0.2977	0.6994	0.3002	0.0002	0.0001
	R-2	0.7010	0.2980	0.6995	0.3001	0.7012	0.2979	0.6993	0.3003	0.0003	0.0001
	R-3	0.7012	0.2979	0.6993	0.3002	0.7014	0.2977	0.6991	0.3004	0.0006	0.0001
	G-1	0.1675	0.7273	0.1678	0.7195	0.1677	0.7272	0.1674	0.7196	0.0006	0.0005
	G-2	0.1704	0.7319	0.1700	0.7251	0.1706	0.7318	0.1697	0.7253	0.0006	0.0004
	G-3	0.1684	0.7272	0.1678	0.7194	0.1686	0.7271	0.1675	0.7196	0.0006	0.0003

	B-1	0.1232	0.0832	0.1249	0.0810	0.1231	0.0834	0.1251	0.0806	0.0002	0.0004
	B-2	0.1249	0.0791	0.1266	0.0769	0.1248	0.0793	0.1267	0.0765	0.0001	0.0002
	B-3	0.1218	0.0875	0.1237	0.0847	0.1217	0.0878	0.1238	0.0844	0.0001	0.0003
	W-1	0.3278	0.3216	0.3353	0.3328	0.3276	0.3215	0.3360	0.3333	0.0025	0.0029
	W-2	0.3197	0.3020	0.3253	0.3117	0.3195	0.3018	0.3258	0.3120	0.0020	0.0020
	W-3	0.2913	0.2733	0.2972	0.2816	0.2911	0.2731	0.2977	0.2819	0.0022	0.0025
	D-1	0.1679	0.7334	0.1671	0.7272	0.1680	0.7333	0.1669	0.7273	0.0003	0.0018
	D-2	0.1550	0.7267	0.1533	0.7192	0.1577	0.7256	0.1533	0.7193	0.0003	0.0006

Based on the temperature-corrected results of the pilot, the drift of the artifact LEDs could be analyzed. Each LED is measured by the pilot two or three times depending on the measurement rounds. The changes of the chromaticity coordinates x and y measured by the pilot for each artifact LED are shown in the following figures, separated to a plot without temperature correction and to a plot after correction. They show that the effect of the temperature correction is noticeable but small compared to the measurement uncertainty because the laboratory condition of the pilot was little changed during the comparison.

The most of the artifact LEDs show a drift much smaller than ± 0.002 for each round that is comparable to the largest measurement uncertainty of the pilot (see Table 4-2 for green LEDs). However, a few LEDs underwent a large drift and should be excluded from the data analysis. The exclusion of the non-stable artifact LEDs is decided by the participant through the procedure of review of relative data.

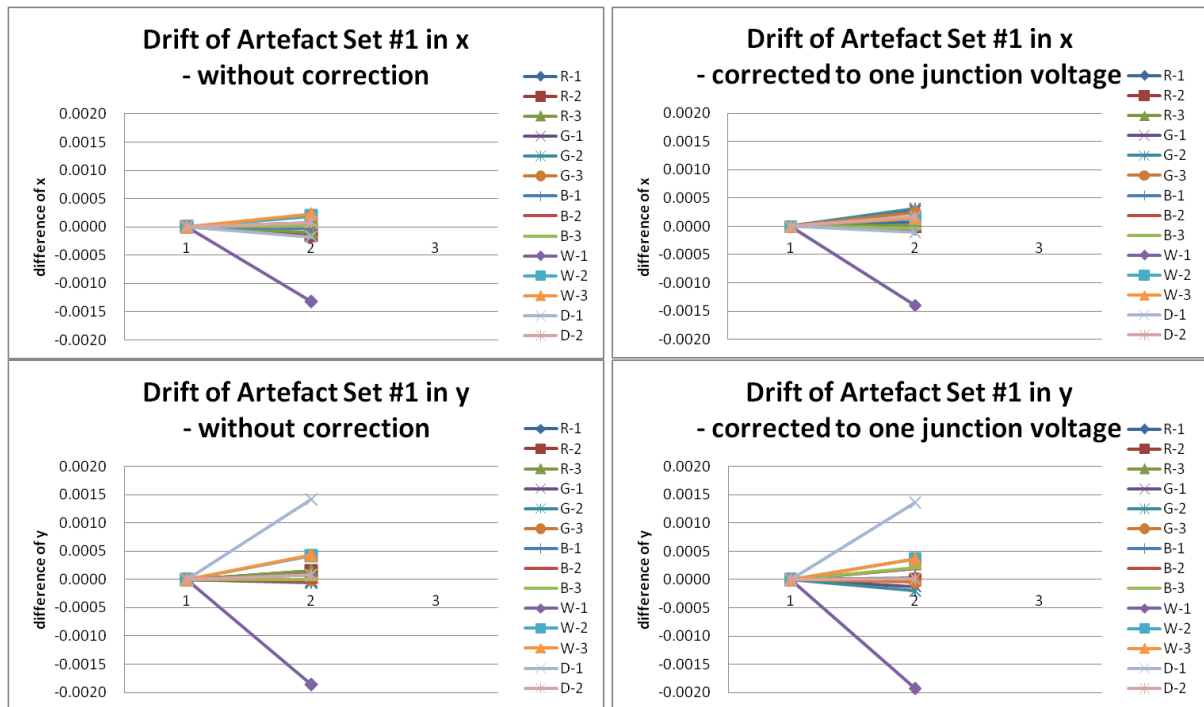


Fig. 6-1. Drift of the artefact set #1.

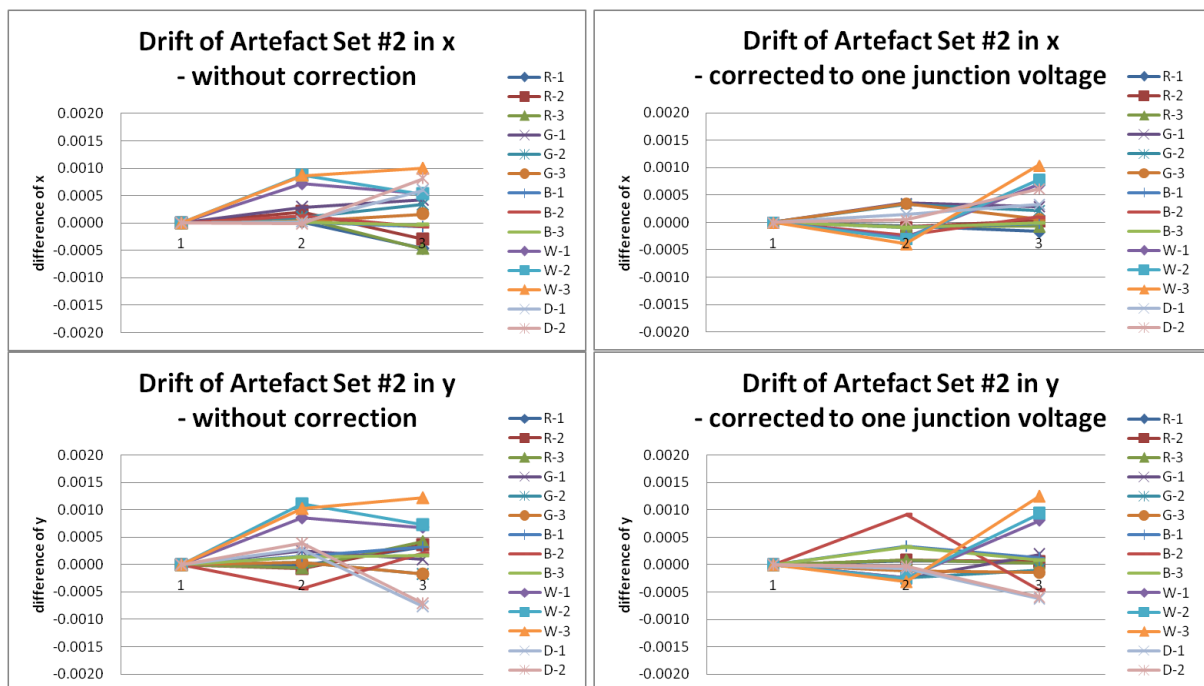


Fig. 6-2. Drift of the artefact set #2.

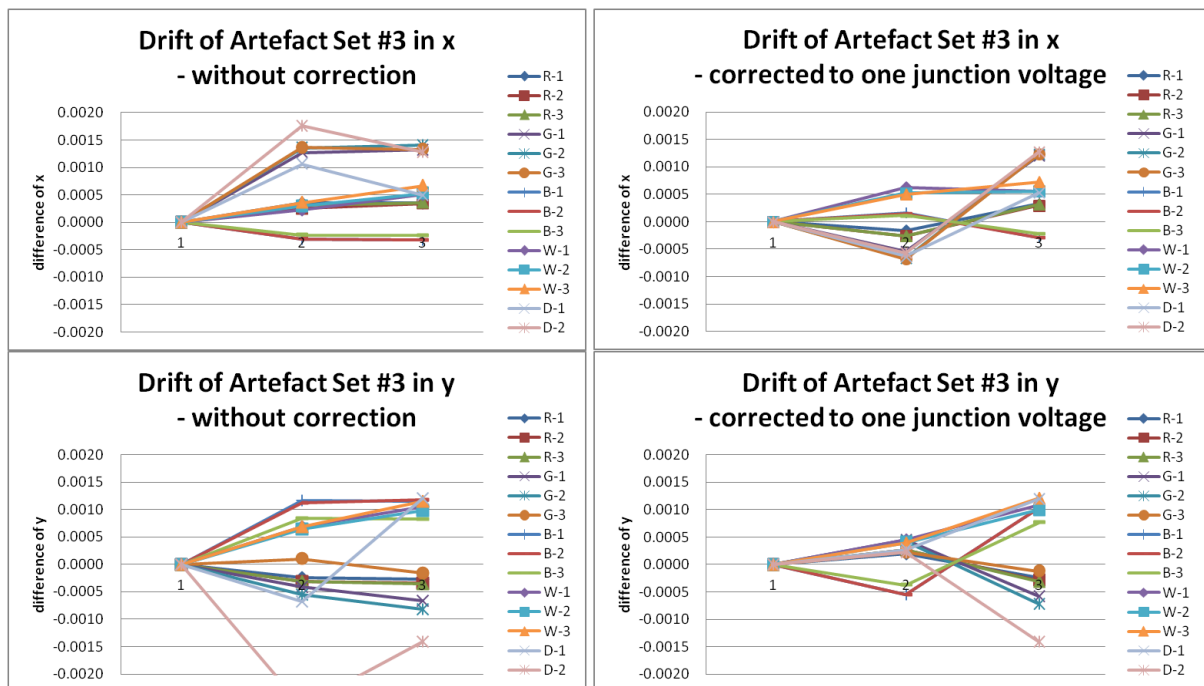


Fig. 6-3. Drift of the artefact set #3.

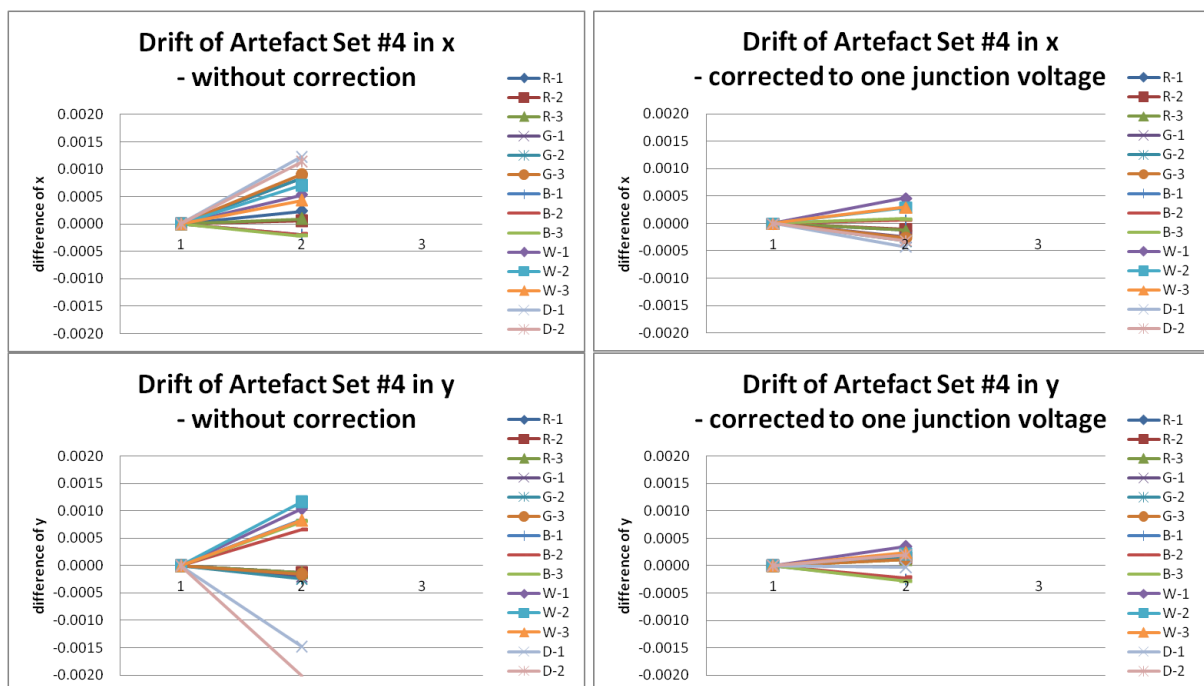


Fig. 6-4. Drift of the artefact set #4.

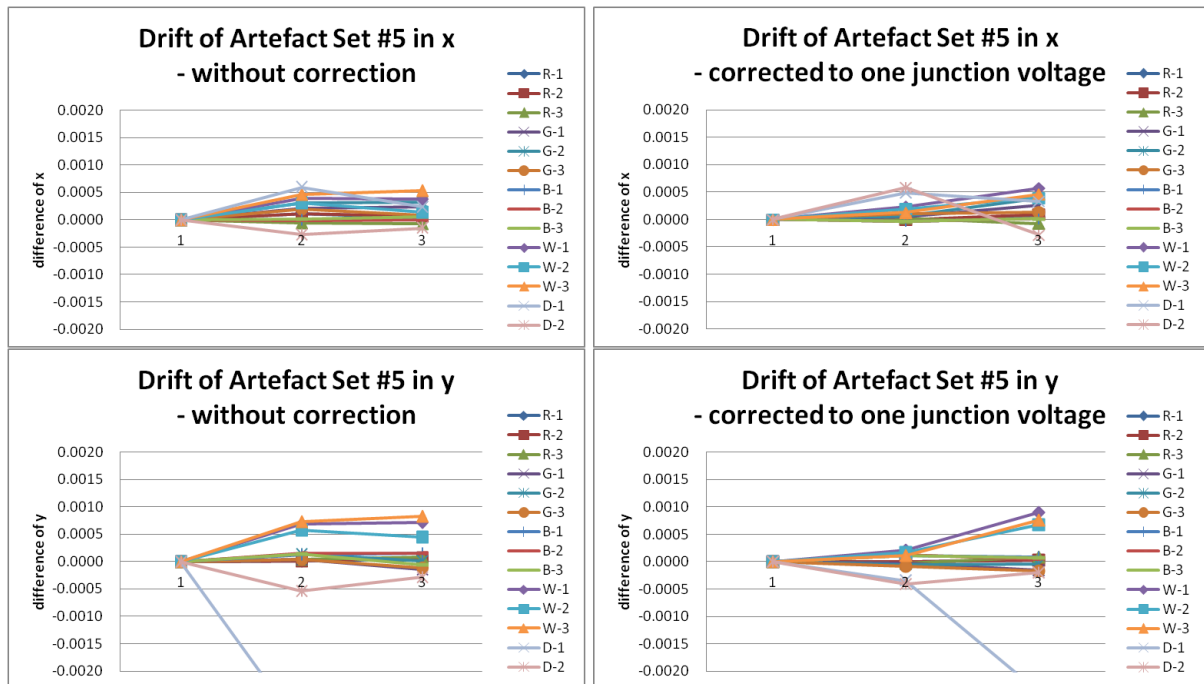


Fig. 6-5. Drift of the artefact set #5.

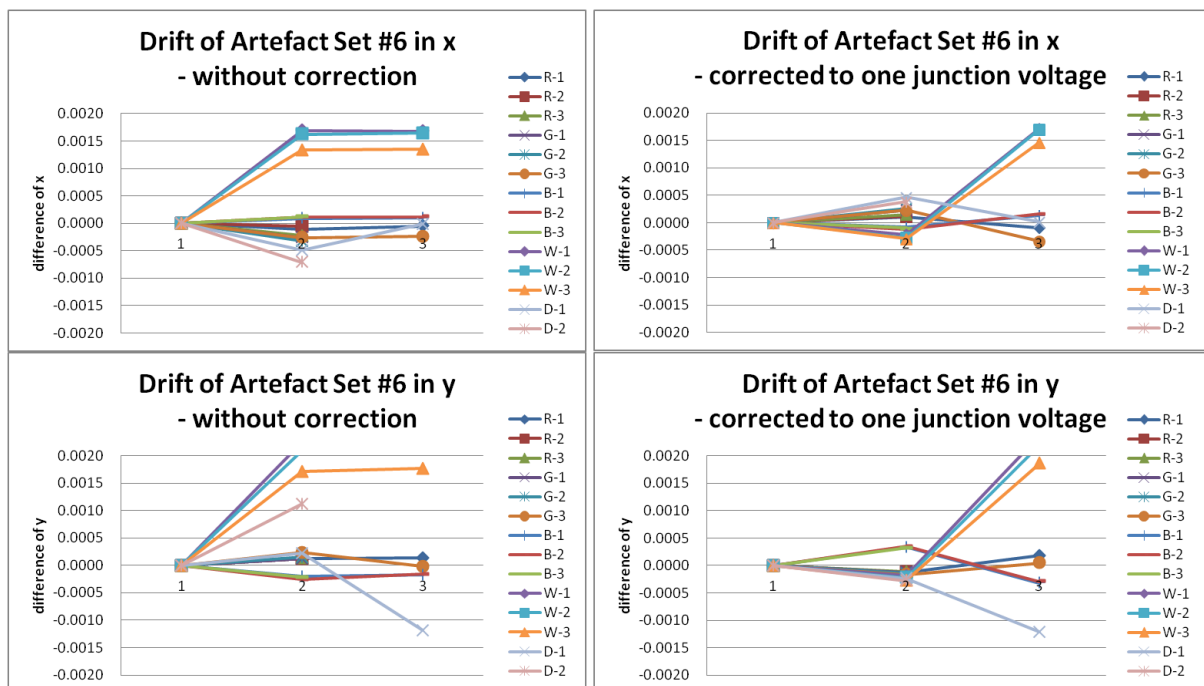


Fig. 6-6. Drift of the artefact set #6.

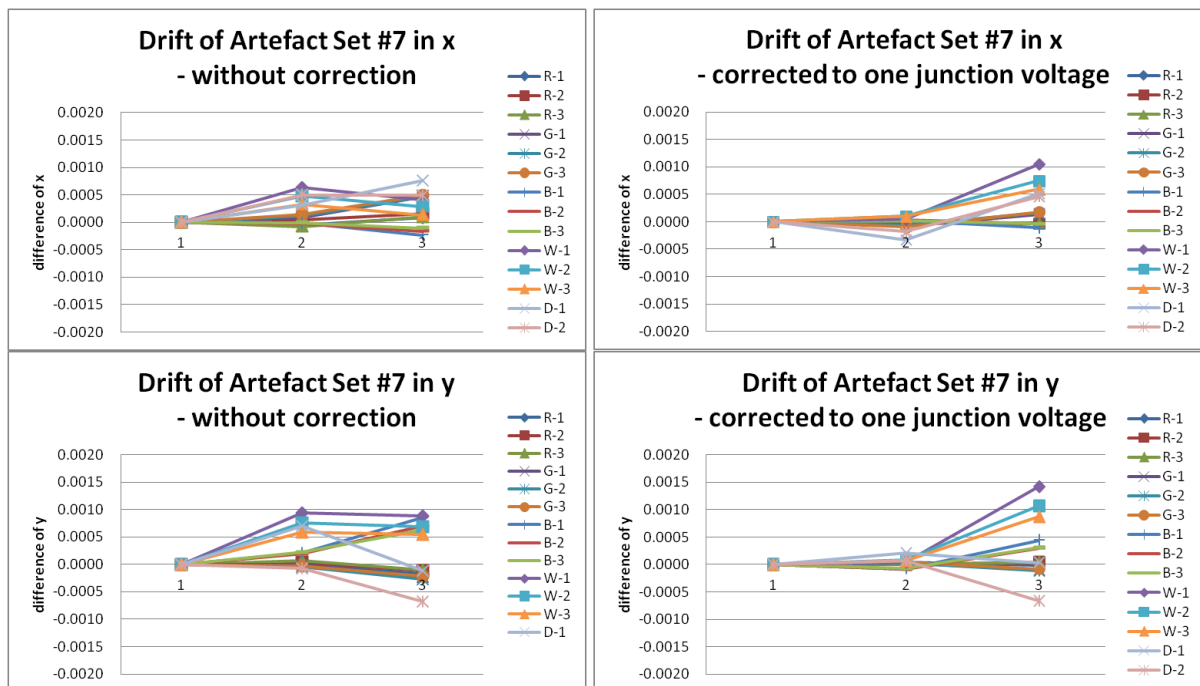


Fig. 6-7. Drift of the artefact set #7.

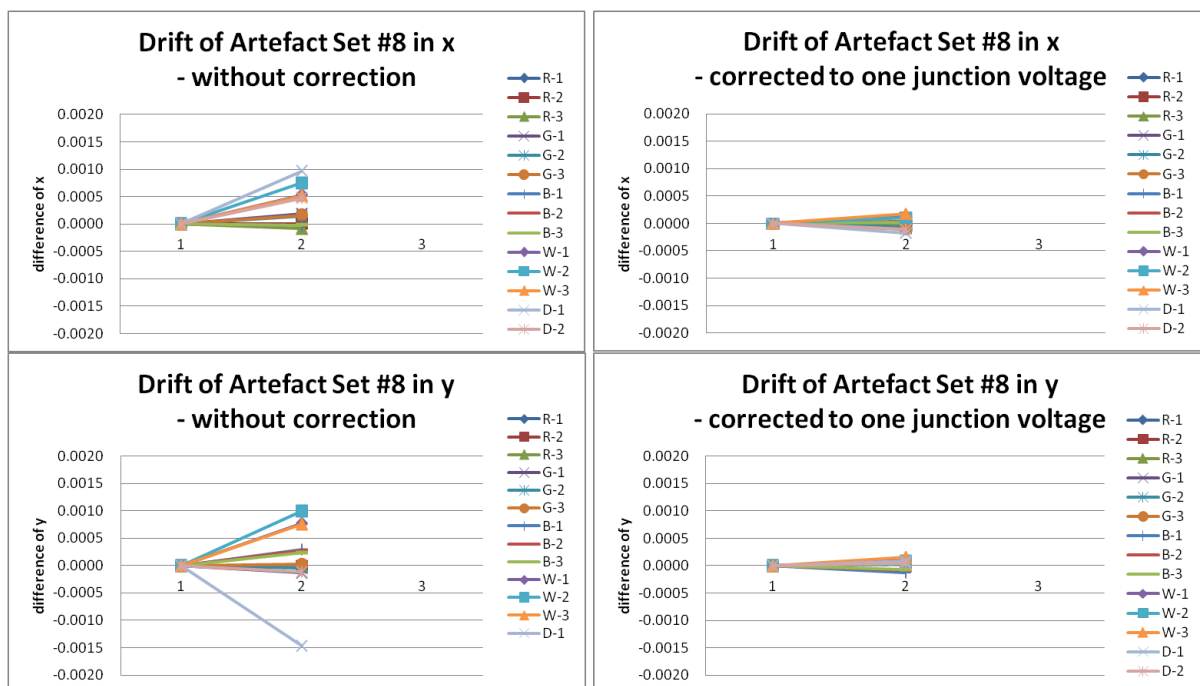


Fig. 6-8. Drift of the artefact set #8.

6.3. Review of Relative Data

The review of relative data started in December 2009. The pilot sent to the participants a document with the relative data of each participant, which are the data reduced to check

only the stability of the artifact LEDs and the internal consistency of each participant. The document circulated for the review of relative data is included in Appendix B: Review of Relative Data as an electronic file. Note that both the uncorrected and temperature-corrected data are separately presented.

The review comments of the participants are collected by the pilot and their summary is included in Appendix C: Comments from Review of Relative Data. As a result of the review of relative data, no LED is excluded in the data analysis of the comparison 3Sc except the following LEDs due to damages during a comparison round.

- #6-R-2/R-3/G-1/G-2/B-3/D-2 measured by MKEH (damaged)

6.4. Review of Uncertainty Budgets

The review of relative data started in March 2010 and completed in June 2010. The pilot summarized the technical reports and uncertainty budgets of the participants to one document and sent it to all the participants. We note that two participants, NMIA and VNIIOFI, could not participate to the review process because their submission of the technical report was delayed for NMIA and abandoned for VNIIOFI. The discussion among the participants and the revisions of the budgets are conducted according to the CCPR Guidelines. The review comments of the participants are collected by the pilot and their summary is included in Appendix D: Comments from Review of Uncertainty Budgets. The final version of the uncertainty budgets is summarized in Chapter 4.

6.5. Identification of Outliers

For the identification of outliers that can significantly skew the reference value of the comparison, the pilot prepared a document with the relative deviation data of each participant from the simple mean values of all the participants without disclosing the participant's identity and the absolute results. The document sent to the participant in June 2010 is included in Appendix E: Identification of Outliers. As a result of the discussion, it was agreed in September 2010 that the data with a relative deviation of more than $\pm 10\%$ from the mean are to identify as outliers. As the measurements of each type (color) of LEDs are taken as each separate comparison, the outlier will be excluded only from the analysis for the related LED type.

7. Data Analysis

The data analysis is performed based on the example in Appendix B of the CCPR Guidelines.¹⁶ However, as the example in the Guidelines was based on a multiplicative model, a modification was required for the chromaticity coordinates data which are better described by an additive model. Also the sequence of each measurement round was “pilot – participant – pilot” in the LED comparison, while “participant – pilot – participant” in the example of the Guidelines. In this chapter, the equations of each analysis step are described. For simplicity, we representatively present the equations for the coordinate x because the equations for the coordinate y are equivalent.

The complete data of the calculation is included as an electronic file (Excel spreadsheet) at the end of the chapter. Note that the analysis is repeated for each type of LEDs, and also for the data without and with the temperature-correction.

7.1. Calculation of Difference to Pilot

For each participant with index i and for each LED with index j , the two measurement results of the pilot (index P), before (index $P1$) and after (index $P2$) the participant, are averaged by

$$x_{i,j}^P = \frac{1}{2}(x_{i,j}^{P1} + x_{i,j}^{P2}). \quad (7-1)$$

As the pilot's uncertainty budget is dominated by the correlated components, the standard uncertainty of the pilot's average value $x_{i,j}^P$ can be calculated from the standard uncertainties of each measurement simply by

$$u(x_{i,j}^P) = \frac{1}{2}[u(x_{i,j}^{P1}) + u(x_{i,j}^{P2})]. \quad (7-2)$$

Note that the pilot reported and applied the upper boundary values for all the uncertainty components in the budgets so that the standard uncertainty of each measurement remained the same for each LED type.

The difference $\Delta_{i,j}$ between the participant i and the pilot (index P) for each LED j is then calculated by

$$\Delta_{i,j} = x_{i,j} - x_{i,j}^P \quad (7-3)$$

and its uncertainty by

$$u(\Delta_{i,j}) = \sqrt{u^2(x_{i,j}) + u^2(x_{i,j}^P) + u_{add}^2(x_{i,j})}. \quad (7-4)$$

¹⁶ CCPR Key Comparison Working Group, *Guidelines for CCPR Comparison Report Preparation*, Rev. 2 (Sept. 18, 2009), available at http://www.bipm.org/en/committees/cc/ccpr/publications_cc.html

Here, $u_{add}(x_{i,j})$ denotes the additional uncertainty in the measurement of LED j by the participant i due to non-ideal characteristics of the artifact LEDs. For the results without temperature correction, we used the drift of the LED for the corresponding round as the value of $u_{add}(x_{i,j})$, which is calculated from the relative difference of the two measurement results of the pilot. For the results with temperature correction, the relative standard uncertainty of the correction procedure in Table 6-1 ~ Table 6-13 is additionally combined to $u_{add}(x_{i,j})$. The standard uncertainty of the participant $u(x_{i,j})$ is determined from the reported expanded results in Chapter 5.

Finally, the results of the multiple LEDs for each type are averaged for the participant i by

$$\Delta_i = \frac{1}{3} \sum_j \Delta_{i,j}. \quad (7-5)$$

Under assumption that the results of multiple LEDs measured by the same participant are strongly correlated, the uncertainty of the relative differences is calculated simply by

$$u(\Delta_i) = \frac{1}{3} \sum_j u(\Delta_{i,j}). \quad (7-6)$$

For the pilot, we use now the index $i = 0$ and set $\Delta_0 = 0$. According to Eq. (7-4), the uncertainty $u(\Delta_0)$ for the pilot is the same as the total standard uncertainty averaged over all the measurements by the pilot. For case of the temperature corrected results, we added also the uncertainty of the correction to $u(\Delta_0)$.

7.2. Calculation of Comparison Reference Value

The Reference Value (RV) of the comparison for each LED type is calculated using weighted mean with cut-off. The cut-off value u_{cut} is calculated by

$$u_{cut} = \text{average}\{u(x_i)\} \text{ for } u(x_i) \leq \text{median}\{u(x_i)\}; \quad i = 0, \dots, N. \quad (7-7)$$

Note that the outliers are not included in the calculation of the RV so that the number N denotes the number of the participants whose comparison results are not identified as outliers (the pilot not counted as a participant here).

The total standard uncertainty $u(x_i)$ of each participant i , averaged over LEDs with different j , is adjusted by the cut-off ($i = 0, \dots, N$):

$$\begin{aligned} u_{adj}(x_i) &= u(x_i) \text{ for } u(x_i) \geq u_{cut} \\ u_{adj}(x_i) &= u_{cut} \text{ otherwise} \end{aligned} \quad (7-8)$$

Also, the uncertainty of Δ_i is adjusted after cut-off by

$$u_{adj}(\Delta_i) = \sqrt{u_{adj}^2(x_i) + u_T^2(\Delta_i)}. \quad (7-9)$$

Here, $u_T(\Delta_i)$ denotes the transfer uncertainty component in $u(\Delta_i)$, which is separated by

$$u_T(\Delta_i) = \sqrt{u^2(\Delta_i) - u^2(x_i)} . \quad (7-10)$$

These uncertainties are used to calculate the weights w_i for each participant i given by

$$w_i = \frac{u_{adj}^{-2}(\Delta_i)}{\sum_{i=0}^N u_{adj}^{-2}(\Delta_i)} . \quad (7-11)$$

Finally, the RV is determined by

$$\Delta_{RV} = \sum_{i=0}^N w_i \Delta_i . \quad (7-12)$$

The uncertainty of the comparison RV is given by

$$u(\Delta_{RV}) = \frac{\sqrt{\sum_{i=0}^N \frac{u^2(\Delta_i)}{u_{adj}^4(\Delta_i)}}}{\sum_{i=0}^N u_{adj}^{-2}(\Delta_i)} . \quad (7-13)$$

7.3. Calculation of Degree of Equivalence

The unilateral degree of equivalence (DoE) of the participant i is defined by

$$D_i = \Delta_i - \Delta_{RV} . \quad (7-14)$$

The DoE is calculated according to Eq. (7-14) also for the participants whose comparison results are identified as outliers. However, the uncertainty of DoE is different. For the participants whose results are included in the calculation of the RV, the uncertainty of DoE is given, as an expanded uncertainty with a coverage factor $k = 2$, by

$$U_i = k \sqrt{u^2(\Delta_i) + u^2(\Delta_{RV}) - 2 \left[\frac{u^2(\Delta_i)}{u_{adj}^2(\Delta_i)} \right] / \sum_{i=0}^N u_{adj}^{-2}(\Delta_i)} . \quad (7-15)$$

For the participants whose results are excluded in the calculation of the RV, the uncertainty of DoE is simplified to

$$U_i = k \sqrt{u^2(\Delta_i) + u^2(\Delta_{RV})} . \quad (7-16)$$

7.4. Data Analysis Spreadsheet

The Excel-file can be opened by a double-click on the icon below.



DoE_color.xlsx

8. Comparison Results

8.1. Red LEDs

The comparison RV for chromaticity coordinates of red LEDs is calculated to be $\Delta_{RV}(x) = 0.0006 \pm 0.0010$, $\Delta_{RV}(y) = -0.0011 \pm 0.0004$ ($k = 2$) for the results without temperature correction, and $\Delta_{RV}(x) = 0.0008 \pm 0.0010$, $\Delta_{RV}(y) = -0.0013 \pm 0.0006$ ($k = 2$) for the results after temperature correction. Table 8-1 and Table 8-2 summarize the comparison results for red LEDs without and with temperature correction, respectively. The last columns of each table shows the E_n criteria of each participant, which is defined as the absolute ratio of D_i and $U(D_i)$. Note that the results of CENAM are identified as outliers and not included in the calculation of the RV.

Table 8-1. Comparison results for red LEDs without temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	0.0016	0.0020	0.0668	0.0010	0.0039	0.256	-0.0014	0.0009	0.0797	-0.0003	0.0017	0.176
CMS-ITRI	0.0005	0.0022	0.0577	-0.0001	0.0042	0.024	-0.0006	0.0023	0.0118	0.0005	0.0047	0.106
PTB	0.0016	0.0017	0.0889	0.0011	0.0033	0.333	-0.0016	0.0009	0.0835	-0.0005	0.0017	0.294
NMIJ	0.0015	0.0017	0.0929	0.0009	0.0032	0.281	-0.0013	0.0008	0.1069	-0.0002	0.0015	0.133
CENAM	-0.1053	0.0067	N.A.	-0.1059	0.0135	7.844	0.0078	0.0010	N.A.	0.0089	0.0023	3.870
LNE	0.0007	0.0039	0.0181	0.0002	0.0076	0.026	-0.0005	0.0017	0.0235	0.0005	0.0033	0.152
METAS	0.0016	0.0016	0.0934	0.0011	0.0031	0.355	-0.0014	0.0007	0.1098	-0.0003	0.0014	0.214
NMC-A*STAR	0.0021	0.0016	0.0935	0.0015	0.0031	0.484	-0.0017	0.0007	0.1101	-0.0006	0.0014	0.429
NMIA	-0.0090	0.0019	0.0764	-0.0096	0.0036	2.667	-0.0002	0.0008	0.1004	0.0008	0.0015	0.533
NIST	0.0018	0.0016	0.0935	0.0013	0.0031	0.419	-0.0015	0.0007	0.1099	-0.0004	0.0014	0.286
VNIOFI	0.0011	0.0018	0.0802	0.0005	0.0035	0.143	-0.0012	0.0011	0.0522	-0.0001	0.0022	0.045
MKEH	0.0011	0.0019	0.0752	0.0006	0.0036	0.167	-0.0008	0.0011	0.0535	0.0003	0.0021	0.143
INM	0.0021	0.0021	0.0590	0.0015	0.0041	0.366	-0.0023	0.0016	0.0262	-0.0012	0.0031	0.387
KRISS	0.0000	0.0016	0.1046	-0.0005	0.0030	0.167	0.0000	0.0007	0.1324	0.0011	0.0013	0.846

Table 8-2. Comparison results for red LEDs after temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	0.0019	0.0020	0.0668	0.0011	0.0039	0.282	-0.0018	0.0009	0.0817	-0.0004	0.0017	0.235
CMS-ITRI	0.0009	0.0021	0.0616	0.0001	0.0041	0.024	-0.0010	0.0023	0.0123	0.0003	0.0046	0.065
PTB	0.0017	0.0018	0.0903	0.0009	0.0033	0.273	-0.0015	0.0008	0.0922	-0.0002	0.0016	0.125
NMIJ	0.0017	0.0018	0.0866	0.0009	0.0034	0.265	-0.0015	0.0008	0.1067	-0.0002	0.0015	0.133
CENAM	-0.1051	0.0068	N.A.	-0.1059	0.0136	7.787	0.0075	0.0011	N.A.	0.0088	0.0024	3.667
LNE	0.0011	0.0039	0.0186	0.0003	0.0077	0.039	-0.0009	0.0017	0.0236	0.0004	0.0033	0.121
METAS	0.0020	0.0017	0.0917	0.0013	0.0032	0.406	-0.0018	0.0007	0.1085	-0.0005	0.0014	0.357

NMC-A*STAR	0.0021	0.0017	0.0930	0.0014	0.0032	0.438	-0.0018	0.0008	0.1067	-0.0005	0.0014	0.357
NMIA	-0.0084	0.0019	0.0772	-0.0091	0.0036	2.528	-0.0009	0.0008	0.0973	0.0004	0.0016	0.250
NIST	0.0018	0.0017	0.0924	0.0010	0.0032	0.313	-0.0014	0.0007	0.1081	-0.0001	0.0014	0.071
VNIIOFI	0.0014	0.0019	0.0782	0.0007	0.0036	0.194	-0.0017	0.0011	0.0509	-0.0004	0.0022	0.182
MKEH	0.0014	0.0019	0.0756	0.0006	0.0037	0.162	-0.0011	0.0011	0.0507	0.0002	0.0022	0.091
INM	0.0023	0.0022	0.0593	0.0015	0.0042	0.357	-0.0025	0.0016	0.0268	-0.0012	0.0031	0.387
KRISS	0.0000	0.0016	0.1087	-0.0007	0.0030	0.233	0.0000	0.0007	0.1347	0.0013	0.0013	1.000

The comparison results for red LEDs without and with temperature correction are plotted in Fig. 8-1 and Fig. 8-2, respectively. The DoEs and its uncertainties are plotted as dot symbols and error bars, respectively. The red lines indicate the expanded uncertainty of the comparison RV.

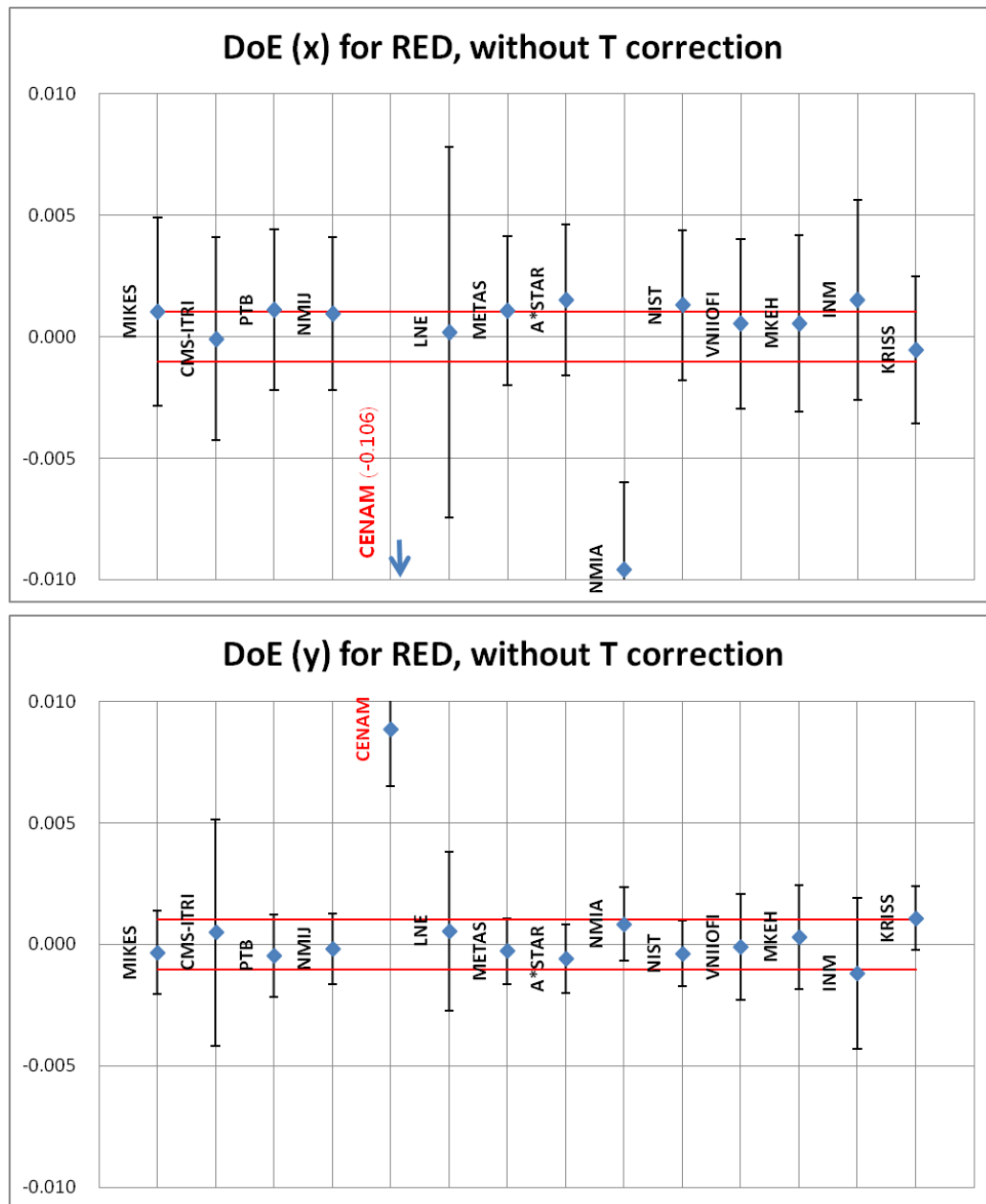


Fig. 8-1. DoE for red LEDs without temperature correction.

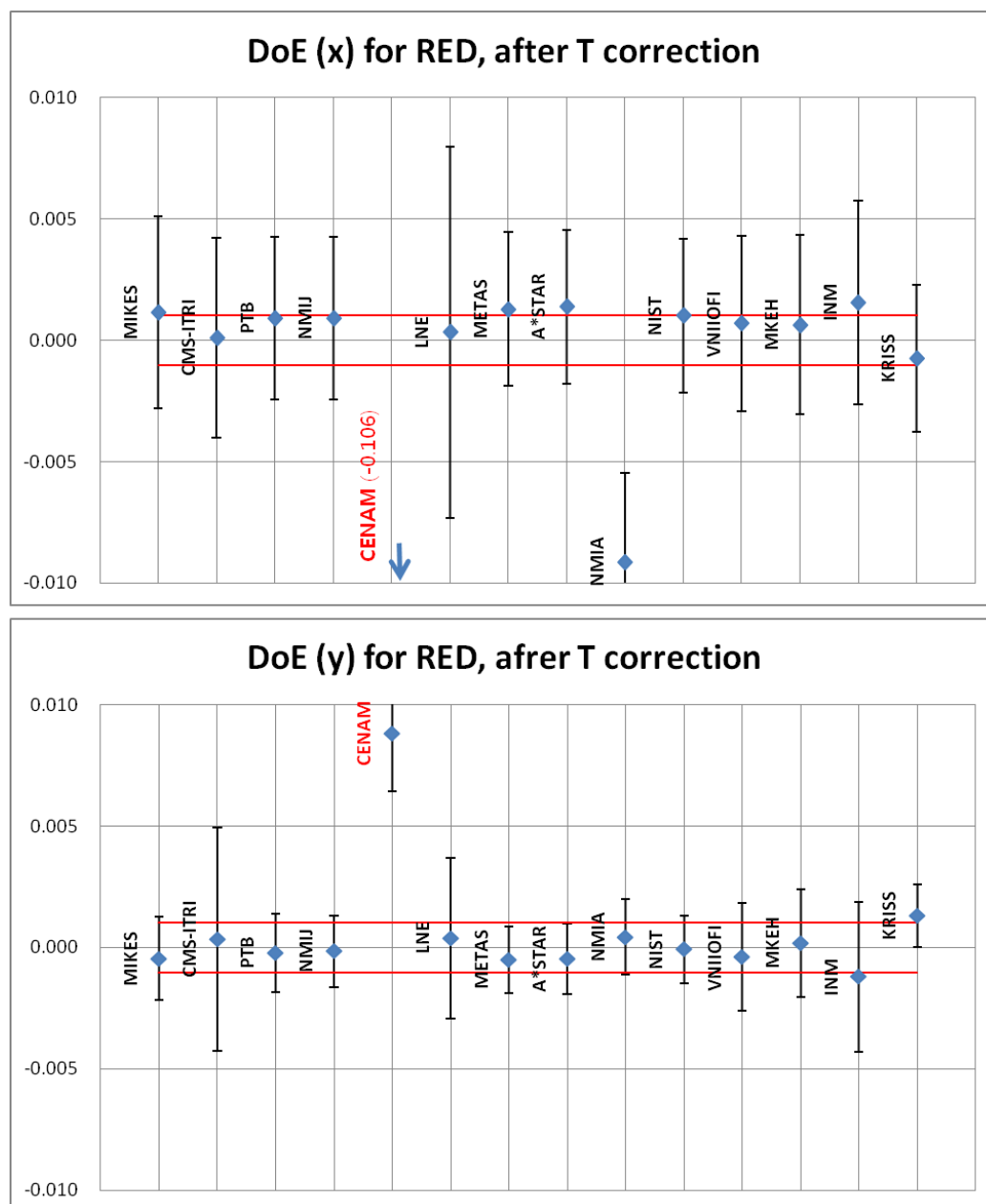


Fig. 8-2. DoE for red LEDs after temperature correction.

8.2. Green LEDs

The comparison RV for chromaticity coordinates of green LEDs is calculated to be $\Delta_{RV}(x) = 0.0021 \pm 0.0016$, $\Delta_{RV}(y) = 0.0049 \pm 0.0014$ ($k = 2$) for the results without temperature correction, and $\Delta_{RV}(x) = 0.0026 \pm 0.0016$, $\Delta_{RV}(y) = 0.0046 \pm 0.0016$ ($k = 2$) for the results after temperature correction. Table 8-3 and Table 8-4 summarize the comparison results for green LEDs without and with temperature correction, respectively. The last columns of each table shows the E_n criteria of each participant, which is defined

as the absolute ratio of D_i and $U(D_i)$. Note that the results of CENAM are identified as outliers and not included in the calculation of the RV.

Table 8-3. Comparison results for green LEDs without temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	0.0025	0.0031	0.0604	0.0004	0.0061	0.066	0.0052	0.0024	0.0897	0.0003	0.0046	0.065
CMS-ITRI	0.0060	0.0033	0.0559	0.0039	0.0063	0.619	0.0080	0.0036	0.0416	0.0031	0.0070	0.443
PTB	0.0033	0.0030	0.0660	0.0012	0.0058	0.207	0.0043	0.0029	0.0629	-0.0005	0.0056	0.089
NMIJ	0.0023	0.0028	0.0765	0.0003	0.0054	0.056	0.0049	0.0026	0.0748	0.0001	0.0051	0.020
CENAM	0.0294	0.0028	N.A.	0.0273	0.0057	4.789	-0.0646	0.0040	N.A.	-0.0694	0.0082	8.463
LNE	0.0015	0.0032	0.0565	-0.0006	0.0063	0.095	0.0040	0.0043	0.0285	-0.0009	0.0085	0.106
METAS	0.0031	0.0025	0.0872	0.0010	0.0049	0.204	0.0045	0.0023	0.0909	-0.0003	0.0044	0.068
NMC-A*STAR	-0.0011	0.0026	0.0851	-0.0032	0.0051	0.627	0.0132	0.0026	0.0793	0.0084	0.0049	1.714
NMIA	-0.0023	0.0025	0.0870	-0.0044	0.0049	0.898	-0.0017	0.0024	0.0878	-0.0066	0.0047	1.404
NIST	0.0028	0.0025	0.0873	0.0007	0.0049	0.143	0.0050	0.0024	0.0899	0.0002	0.0045	0.044
VNIOFI	0.0048	0.0027	0.0812	0.0027	0.0052	0.519	0.0059	0.0025	0.0857	0.0010	0.0047	0.213
MKEH	0.0059	0.0027	0.0832	0.0038	0.0051	0.745	0.0050	0.0024	0.0895	0.0002	0.0046	0.043
INM	0.0004	0.0028	0.0784	-0.0017	0.0053	0.321	0.0074	0.0026	0.0802	0.0025	0.0049	0.510
KRISS	0.0000	0.0025	0.0953	-0.0021	0.0048	0.438	0.0000	0.0023	0.0992	-0.0049	0.0044	1.114

Table 8-4. Comparison results for green LEDs after temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	0.0032	0.0033	0.0609	0.0005	0.0064	0.078	0.0049	0.0025	0.0922	0.0004	0.0047	0.085
CMS-ITRI	0.0069	0.0035	0.0543	0.0042	0.0068	0.618	0.0075	0.0037	0.0409	0.0029	0.0073	0.397
PTB	0.0031	0.0033	0.0610	0.0005	0.0064	0.078	0.0045	0.0032	0.0575	0.0000	0.0061	0.000
NMIJ	0.0026	0.0032	0.0637	0.0000	0.0063	0.000	0.0048	0.0027	0.0772	0.0002	0.0052	0.038
CENAM	0.0303	0.0028	N.A.	0.0277	0.0059	4.695	-0.0652	0.0041	N.A.	-0.0698	0.0083	8.410
LNE	0.0019	0.0033	0.0633	-0.0007	0.0063	0.111	0.0037	0.0043	0.0307	-0.0009	0.0085	0.106
METAS	0.0038	0.0026	0.0930	0.0011	0.0050	0.220	0.0043	0.0024	0.0961	-0.0003	0.0045	0.067
NMC-A*STAR	-0.0011	0.0028	0.0835	-0.0037	0.0054	0.685	0.0132	0.0028	0.0738	0.0087	0.0054	1.611
NMIA	-0.0008	0.0028	0.0818	-0.0034	0.0053	0.642	-0.0026	0.0027	0.0791	-0.0072	0.0052	1.385
NIST	0.0025	0.0031	0.0667	-0.0001	0.0060	0.017	0.0052	0.0027	0.0765	0.0006	0.0052	0.115
VNIOFI	0.0060	0.0028	0.0877	0.0034	0.0053	0.642	0.0050	0.0026	0.0877	0.0005	0.0049	0.102
MKEH	0.0067	0.0027	0.0915	0.0040	0.0052	0.769	0.0045	0.0024	0.0949	-0.0001	0.0046	0.022
INM	0.0008	0.0028	0.0854	-0.0018	0.0054	0.333	0.0072	0.0026	0.0855	0.0026	0.0049	0.531
KRISS	0.0000	0.0025	0.1072	-0.0026	0.0047	0.553	0.0000	0.0023	0.1079	-0.0046	0.0043	1.070

The comparison results for green LEDs without and with temperature correction are plotted in Fig. 8-3 and Fig. 8-4, respectively. The DoEs and its uncertainties are plotted as dot symbols and error bars, respectively. The red lines indicate the expanded uncertainty

of the comparison RV.

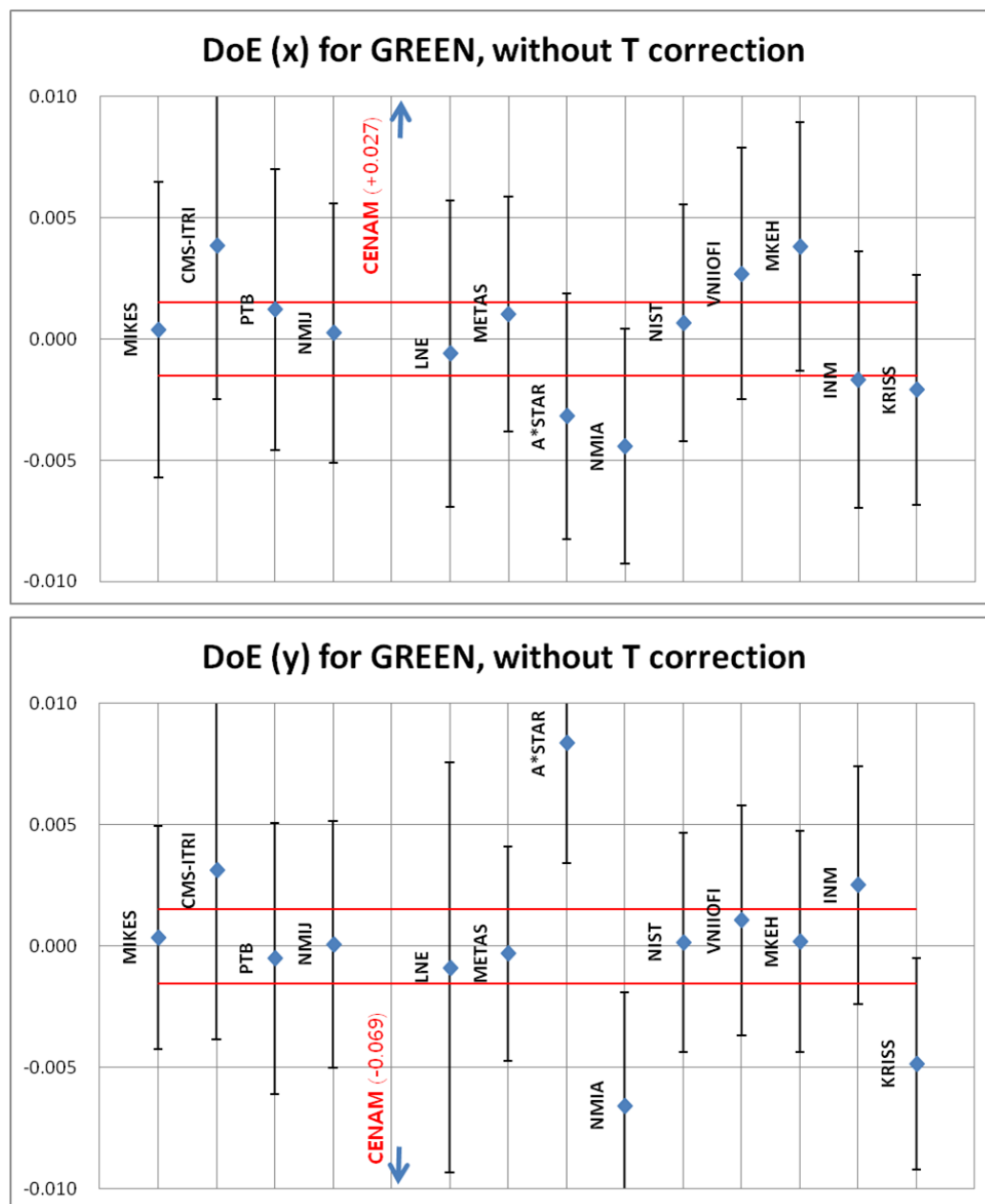


Fig. 8-3. DoE for green LEDs without temperature correction.

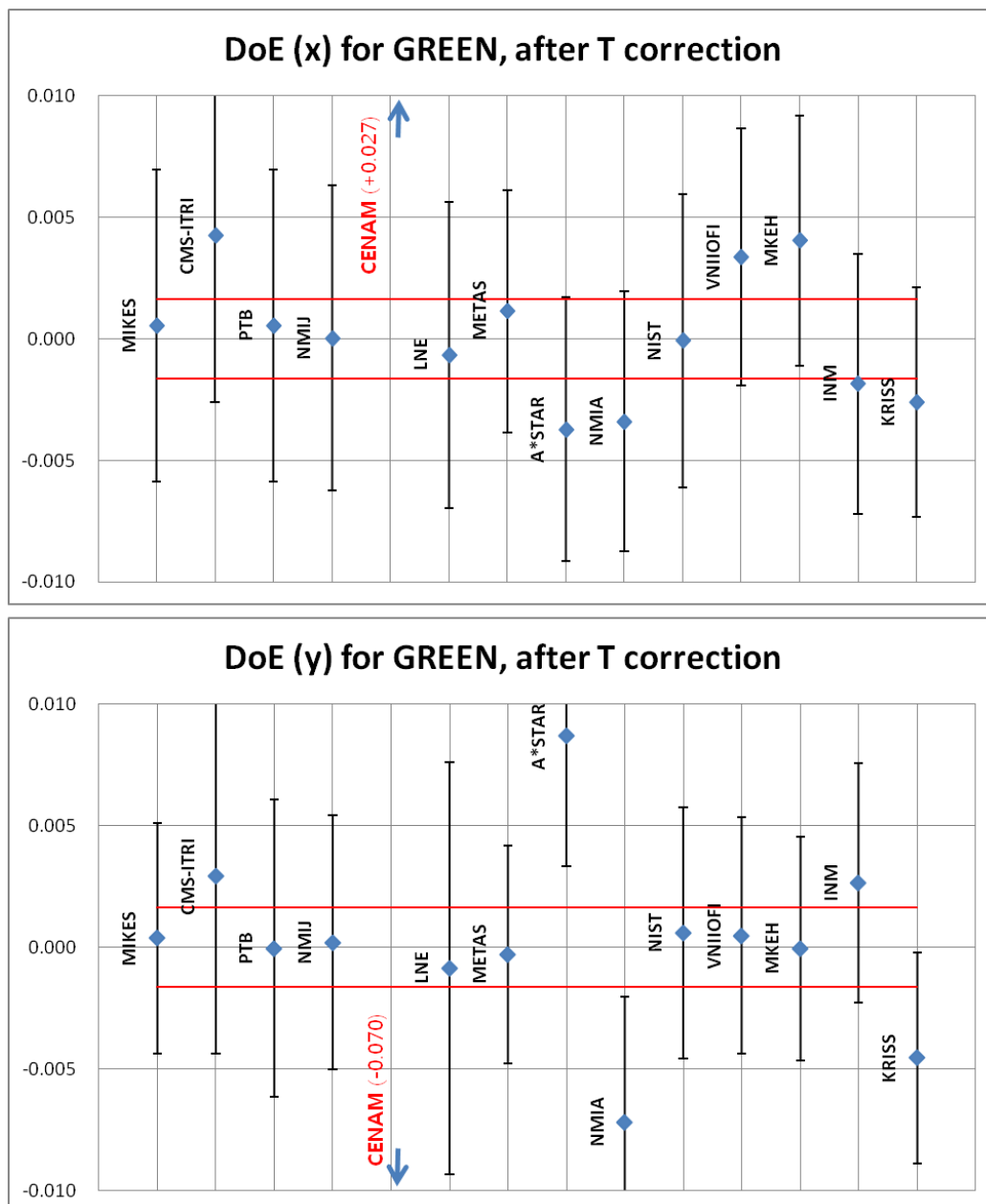


Fig. 8-4. DoE for green LEDs after temperature correction.

8.3. Blue LEDs

The comparison RV for chromaticity coordinates of blue LEDs is calculated to be $\Delta_{RV}(x) = -0.0012 \pm 0.0006$, $\Delta_{RV}(y) = 0.0026 \pm 0.0012$ ($k=2$) for the results without temperature correction, and $\Delta_{RV}(x) = -0.0014 \pm 0.0006$, $\Delta_{RV}(y) = 0.0031 \pm 0.0012$ ($k=2$) for the results after temperature correction. Table 8-5 and Table 8-6 summarize the comparison results for blue LEDs without and with temperature correction, respectively. The last columns of each table shows the E_n criteria of each participant, which is defined

as the absolute ratio of D_i and $U(D_i)$. Note that the results of CENAM are identified as outliers and not included in the calculation of the RV.

Table 8-5. Comparison results for blue LEDs without temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	-0.0018	0.0011	0.0699	-0.0006	0.0022	0.273	0.0028	0.0022	0.0769	0.0002	0.0042	0.048
CMS-ITRI	-0.0038	0.0018	0.0268	-0.0025	0.0036	0.694	0.0069	0.0030	0.0391	0.0042	0.0060	0.700
PTB	-0.0016	0.0010	0.0865	-0.0004	0.0020	0.200	0.0028	0.0023	0.0707	0.0002	0.0044	0.045
NMIJ	-0.0013	0.0010	0.0909	-0.0001	0.0019	0.053	0.0031	0.0022	0.0773	0.0005	0.0042	0.119
CENAM	0.0119	0.0016	N.A.	0.0131	0.0033	3.970	0.0037	0.0024	N.A.	0.0011	0.0049	0.224
LNE	-0.0012	0.0012	0.0657	0.0001	0.0023	0.043	0.0009	0.0027	0.0497	-0.0017	0.0053	0.321
METAS	-0.0013	0.0009	0.0948	0.0000	0.0017	0.000	0.0040	0.0019	0.0911	0.0014	0.0037	0.378
NMC-A*STAR	-0.0023	0.0009	0.0948	-0.0011	0.0018	0.611	0.0038	0.0021	0.0839	0.0012	0.0040	0.300
NMIA	0.0013	0.0010	0.0932	0.0026	0.0018	1.444	-0.0031	0.0020	0.0889	-0.0058	0.0038	1.526
NIST	-0.0018	0.0009	0.0948	-0.0006	0.0018	0.333	0.0027	0.0019	0.0920	0.0001	0.0037	0.027
VNIIOFI	-0.0028	0.0013	0.0561	-0.0015	0.0025	0.600	0.0053	0.0022	0.0761	0.0027	0.0042	0.643
MKEH	-0.0006	0.0011	0.0699	0.0006	0.0022	0.273	0.0048	0.0021	0.0828	0.0022	0.0040	0.550
INM	-0.0019	0.0014	0.0444	-0.0006	0.0028	0.214	0.0027	0.0023	0.0711	0.0000	0.0044	0.000
KRISS	0.0000	0.0009	0.1122	0.0012	0.0017	0.706	0.0000	0.0019	0.1005	-0.0026	0.0036	0.722

Table 8-6. Comparison results for blue LEDs after temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	-0.0021	0.0011	0.0692	-0.0007	0.0022	0.318	0.0035	0.0022	0.0750	0.0004	0.0042	0.095
CMS-ITRI	-0.0040	0.0018	0.0267	-0.0026	0.0036	0.722	0.0076	0.0031	0.0377	0.0045	0.0060	0.750
PTB	-0.0016	0.0010	0.0915	-0.0002	0.0019	0.105	0.0027	0.0021	0.0820	-0.0003	0.0040	0.075
NMIJ	-0.0014	0.0010	0.0912	0.0000	0.0019	0.000	0.0034	0.0021	0.0796	0.0004	0.0041	0.098
CENAM	0.0116	0.0016	N.A.	0.0129	0.0033	3.909	0.0047	0.0024	N.A.	0.0017	0.0049	0.347
LNE	-0.0013	0.0012	0.0658	0.0000	0.0023	0.000	0.0016	0.0027	0.0493	-0.0015	0.0053	0.283
METAS	-0.0015	0.0009	0.0927	-0.0001	0.0018	0.056	0.0047	0.0020	0.0885	0.0017	0.0038	0.447
NMC-A*STAR	-0.0023	0.0010	0.0938	-0.0009	0.0018	0.500	0.0038	0.0021	0.0811	0.0007	0.0040	0.175
NMIA	0.0010	0.0010	0.0928	0.0024	0.0019	1.263	-0.0021	0.0019	0.0894	-0.0051	0.0037	1.378
NIST	-0.0018	0.0009	0.0944	-0.0004	0.0018	0.222	0.0025	0.0019	0.0900	-0.0005	0.0037	0.135
VNIIOFI	-0.0031	0.0013	0.0558	-0.0018	0.0025	0.720	0.0066	0.0022	0.0744	0.0036	0.0042	0.857
MKEH	-0.0008	0.0011	0.0692	0.0005	0.0022	0.227	0.0055	0.0021	0.0812	0.0025	0.0040	0.625
INM	-0.0020	0.0014	0.0445	-0.0006	0.0028	0.214	0.0031	0.0022	0.0725	0.0000	0.0043	0.000
KRISS	0.0000	0.0009	0.1124	0.0014	0.0017	0.824	0.0000	0.0019	0.0993	-0.0031	0.0036	0.861

The comparison results for blue LEDs without and with temperature correction are plotted in Fig. 8-5 and Fig. 8-6, respectively. The DoEs and its uncertainties are plotted as dot symbols and error bars, respectively. The red lines indicate the expanded uncertainty

of the comparison RV.

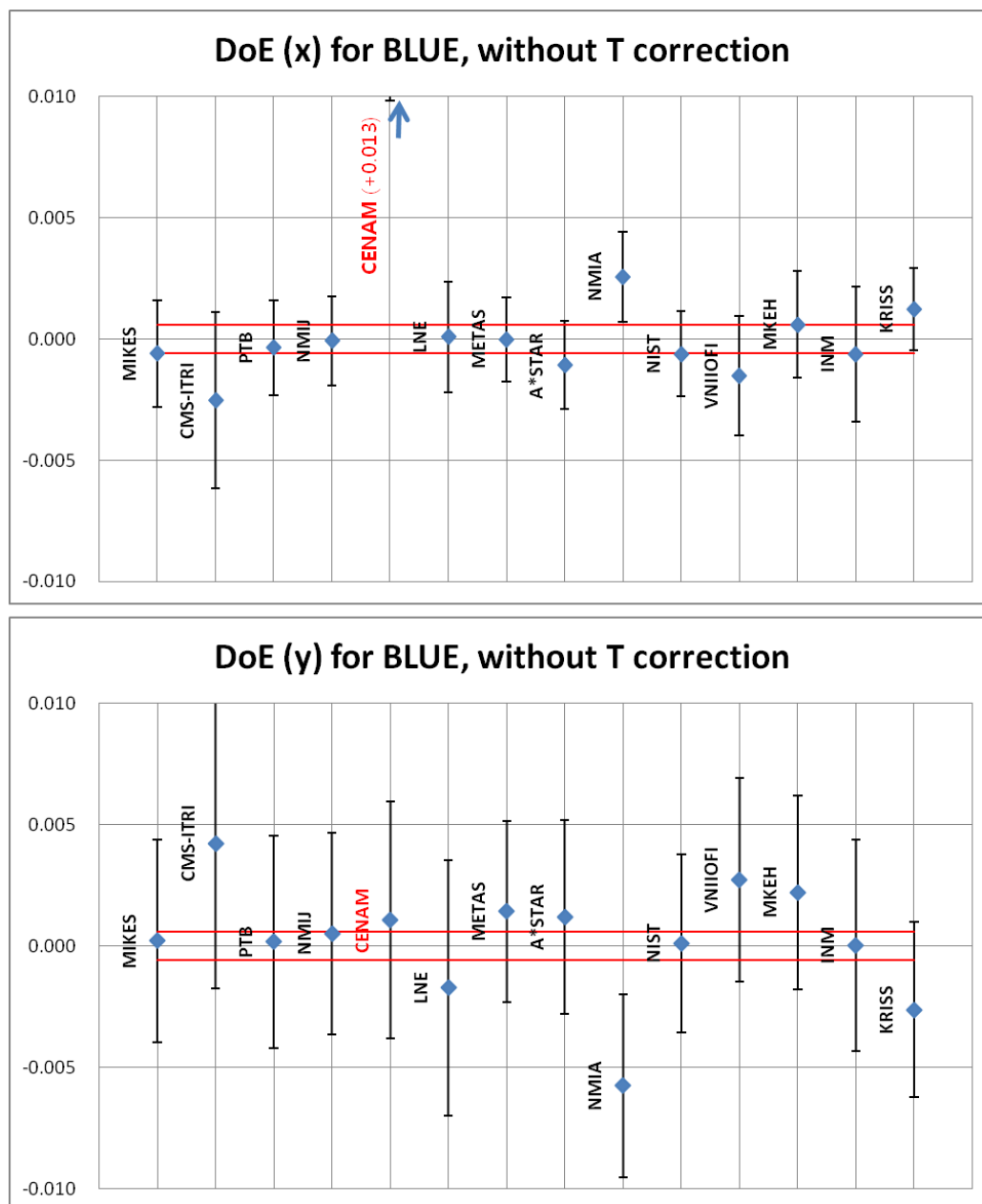


Fig. 8-5. DoE for blue LEDs without temperature correction.

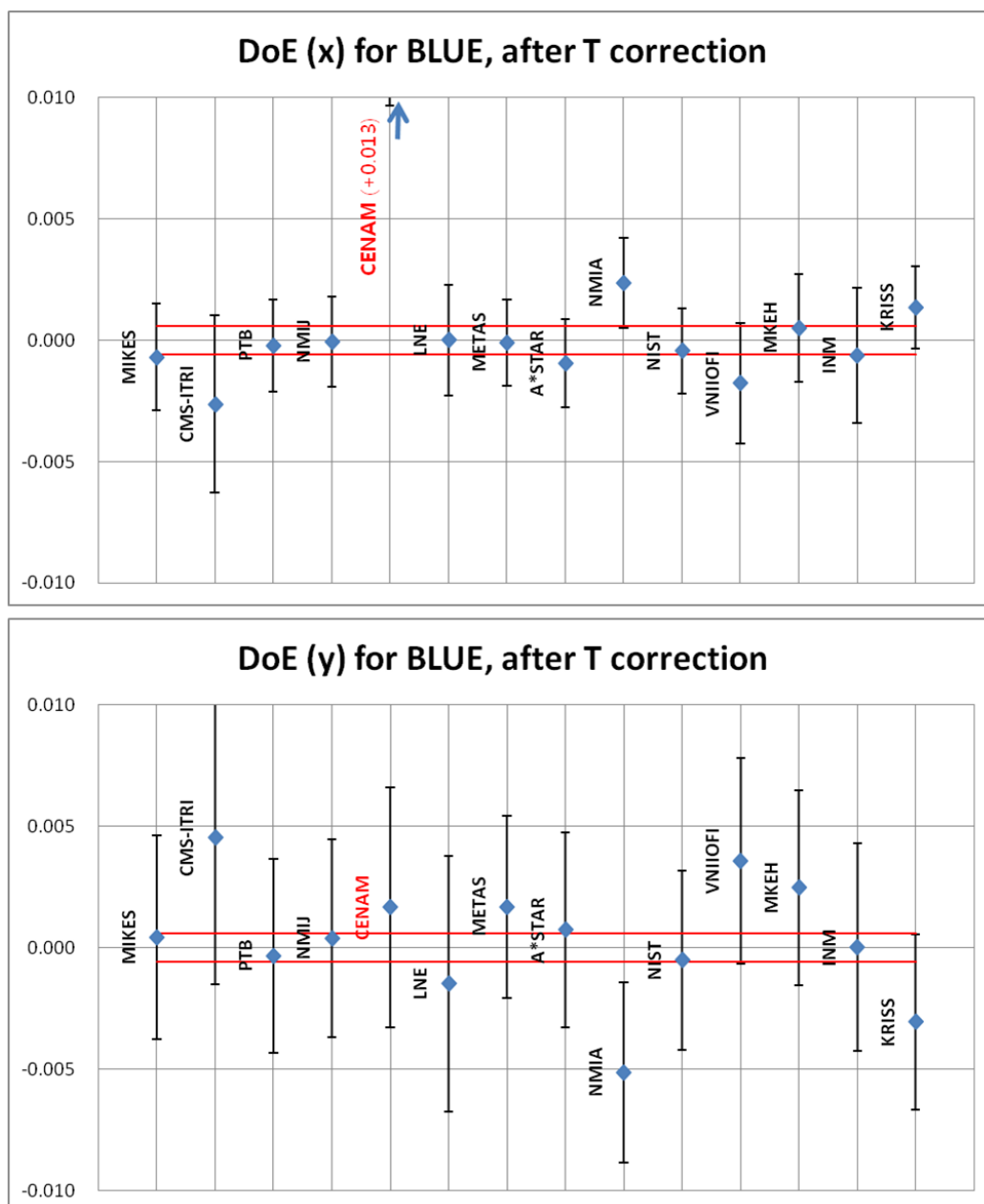


Fig. 8-6. DoE for blue LEDs after temperature correction.

8.4. White LEDs

The comparison RV for chromaticity coordinates of white LEDs is calculated to be $\Delta_{RV}(x) = -0.0007 \pm 0.0006$, $\Delta_{RV}(y) = -0.0024 \pm 0.0006$ ($k=2$) for the results without temperature correction, and $\Delta_{RV}(x) = -0.0005 \pm 0.0010$, $\Delta_{RV}(y) = -0.0020 \pm 0.0010$ ($k=2$) for the results after temperature correction. Table 8-7 and Table 8-8 summarize the comparison results for white LEDs without and with temperature correction, respectively. The last columns of each table shows the E_n criteria of each participant, which is defined

as the absolute ratio of D_i and $U(D_i)$. Note that no result is identified as outlier in this case.

Table 8-7. Comparison results for white LEDs without temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	0.0024	0.0055	0.0036	0.0031	0.0109	0.284	0.0014	0.0082	0.0019	0.0037	0.0164	0.226
CMS-ITRI	0.0007	0.0029	0.0126	0.0014	0.0058	0.241	0.0009	0.0028	0.0161	0.0032	0.0056	0.571
PTB	-0.0002	0.0012	0.0748	0.0004	0.0023	0.174	-0.0006	0.0015	0.0582	0.0017	0.0029	0.586
NMIJ	-0.0032	0.0012	0.0750	-0.0025	0.0023	1.087	-0.0031	0.0016	0.0514	-0.0008	0.0031	0.258
CENAM	0.0063	0.0010	0.1019	0.0070	0.0019	3.684	-0.0104	0.0011	0.0863	-0.0081	0.0022	3.682
LNE	0.0004	0.0031	0.0111	0.0011	0.0062	0.177	-0.0006	0.0046	0.0061	0.0017	0.0091	0.187
METAS	-0.0001	0.0010	0.0942	0.0006	0.0019	0.316	-0.0004	0.0012	0.0786	0.0019	0.0023	0.826
NMC-A*STAR	-0.0008	0.0011	0.0833	-0.0001	0.0022	0.045	-0.0006	0.0014	0.0692	0.0018	0.0026	0.692
NMIA	-0.0051	0.0009	0.1123	-0.0044	0.0017	2.588	-0.0046	0.0009	0.1159	-0.0023	0.0017	1.353
NIST	0.0003	0.0010	0.1099	0.0010	0.0018	0.556	0.0000	0.0010	0.1075	0.0024	0.0019	1.263
VNIOFI	0.0010	0.0012	0.0742	0.0017	0.0023	0.739	0.0019	0.0012	0.0892	0.0043	0.0023	1.870
MKEH	-0.0081	0.0018	0.0317	-0.0074	0.0036	2.056	-0.0046	0.0014	0.0660	-0.0022	0.0027	0.815
INM	-0.0065	0.0015	0.0458	-0.0058	0.0030	1.933	-0.0098	0.0015	0.0546	-0.0074	0.0030	2.467
KRISS	0.0000	0.0008	0.1695	0.0007	0.0015	0.467	0.0000	0.0008	0.1991	0.0024	0.0014	1.714

Table 8-8. Comparison results for white LEDs after temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	0.0015	0.0055	0.0068	0.0020	0.0110	0.182	0.0006	0.0083	0.0032	0.0026	0.0165	0.158
CMS-ITRI	-0.0004	0.0034	0.0177	0.0001	0.0068	0.015	0.0000	0.0033	0.0202	0.0020	0.0065	0.308
PTB	0.0000	0.0018	0.0653	0.0005	0.0034	0.147	-0.0007	0.0019	0.0606	0.0013	0.0037	0.351
NMIJ	-0.0035	0.0024	0.0350	-0.0030	0.0048	0.625	-0.0034	0.0025	0.0355	-0.0013	0.0049	0.265
CENAM	0.0053	0.0014	0.1082	0.0058	0.0026	2.231	-0.0113	0.0014	0.0952	-0.0093	0.0028	3.321
LNE	-0.0003	0.0034	0.0182	0.0002	0.0067	0.030	-0.0012	0.0048	0.0095	0.0009	0.0095	0.095
METAS	-0.0008	0.0025	0.0333	-0.0003	0.0049	0.061	-0.0010	0.0028	0.0281	0.0010	0.0054	0.185
NMC-A*STAR	-0.0008	0.0016	0.0832	-0.0003	0.0030	0.100	-0.0006	0.0019	0.0629	0.0015	0.0036	0.417
NMIA	-0.0066	0.0020	0.0486	-0.0061	0.0040	1.525	-0.0059	0.0020	0.0502	-0.0038	0.0039	0.974
NIST	0.0005	0.0014	0.0977	0.0010	0.0027	0.370	0.0001	0.0013	0.1146	0.0022	0.0025	0.880
VNIOFI	-0.0006	0.0015	0.0969	-0.0001	0.0028	0.036	0.0005	0.0014	0.1080	0.0025	0.0027	0.926
MKEH	-0.0089	0.0024	0.0360	-0.0084	0.0047	1.787	-0.0053	0.0022	0.0449	-0.0033	0.0043	0.767
INM	-0.0069	0.0027	0.0279	-0.0064	0.0054	1.185	-0.0101	0.0029	0.0256	-0.0081	0.0058	1.397
KRISS	0.0000	0.0008	0.3252	0.0005	0.0013	0.385	0.0000	0.0008	0.3414	0.0020	0.0013	1.538

The comparison results for white LEDs without and with temperature correction are plotted in Fig. 8-7 and Fig. 8-8, respectively. The DoEs and its uncertainties are plotted as dot symbols and error bars, respectively. The red lines indicate the expanded uncertainty

of the comparison RV.

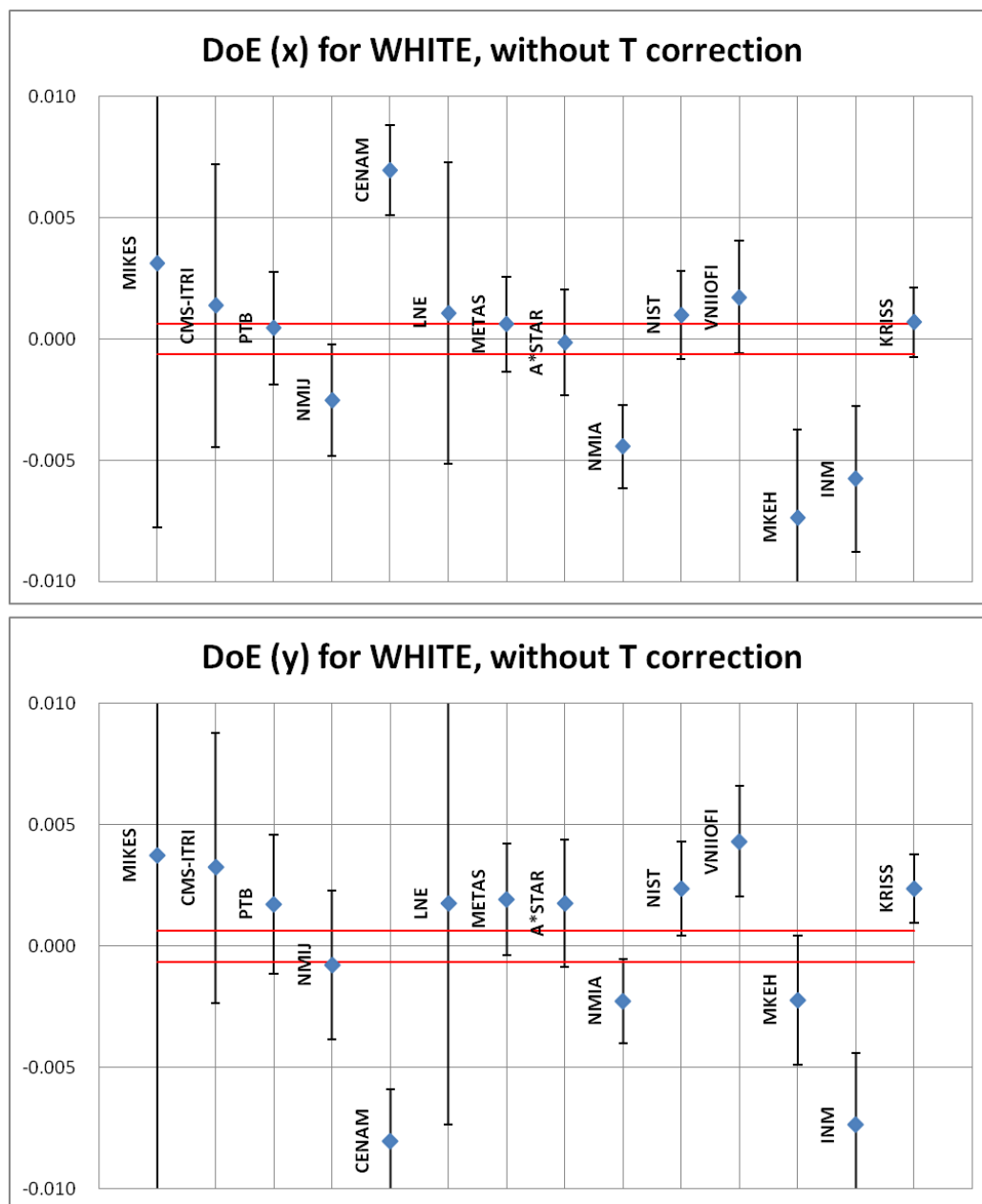


Fig. 8-7. DoE for white LEDs without temperature correction.

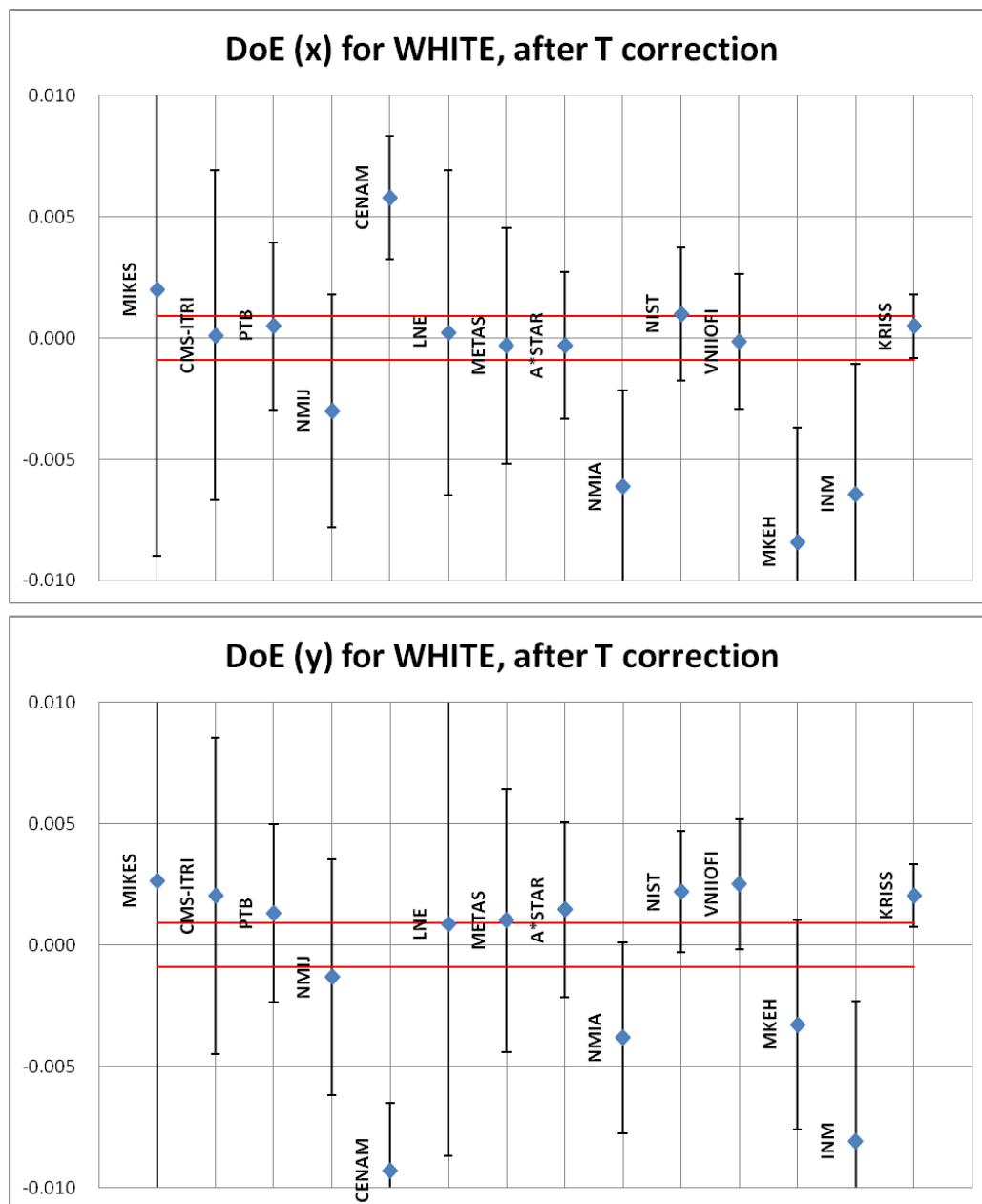


Fig. 8-8. DoE for white LEDs after temperature correction.

8.5. Diffuser-type Green LEDs

The comparison RV for chromaticity coordinates of diffuser-type green LEDs is calculated to be $\Delta_{RV}(x) = 0.0026 \pm 0.0018$, $\Delta_{RV}(y) = 0.0032 \pm 0.0018$ ($k = 2$) for the results without temperature correction, and $\Delta_{RV}(x) = 0.0030 \pm 0.0018$, $\Delta_{RV}(y) = 0.0030 \pm 0.0020$ ($k = 2$) for the results after temperature correction. Table 8-9 and Table 8-10 summarize the comparison results for diffuser-type green LEDs without and with temperature correction, respectively. The last columns of each table shows the E_n criteria of each participant,

which is defined as the absolute ratio of D_i and $U(D_i)$. Note that the results of CENAM are identified as outliers and not included in the calculation of the RV. LNE is not participated to the comparison of this LED type.

Table 8-9. Comparison results for diffuser-type green LEDs without temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	0.0043	0.0070	0.0165	0.0017	0.0138	0.123	0.0024	0.0073	0.0152	-0.0008	0.0146	0.055
CMS-ITRI	0.0089	0.0103	0.0075	0.0063	0.0205	0.307	0.0057	0.0095	0.0090	0.0026	0.0190	0.137
PTB	0.0040	0.0030	0.0876	0.0014	0.0058	0.241	0.0020	0.0033	0.0752	-0.0012	0.0063	0.190
NMIJ	0.0049	0.0029	0.0967	0.0022	0.0055	0.400	-0.0011	0.0031	0.0832	-0.0043	0.0060	0.717
CENAM	0.0542	0.0036	N.A.	0.0516	0.0075	6.880	-0.1404	0.0082	N.A.	-0.1436	0.0166	8.651
LNE	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
METAS	0.0036	0.0034	0.0689	0.0010	0.0066	0.152	0.0035	0.0037	0.0603	0.0003	0.0071	0.042
NMC-A*STAR	-0.0005	0.0028	0.1010	-0.0031	0.0053	0.585	0.0125	0.0030	0.0888	0.0093	0.0058	1.603
NMIA	-0.0009	0.0026	0.1086	-0.0036	0.0050	0.720	0.0022	0.0026	0.1124	-0.0010	0.0048	0.208
NIST	0.0036	0.0026	0.1122	0.0010	0.0049	0.204	0.0027	0.0028	0.0952	-0.0005	0.0054	0.093
VNIIOFI	0.0065	0.0028	0.0990	0.0039	0.0054	0.722	0.0018	0.0025	0.1268	-0.0014	0.0047	0.298
MKEH	0.0055	0.0034	0.0680	0.0028	0.0066	0.424	0.0037	0.0036	0.0627	0.0005	0.0070	0.071
INM	0.0013	0.0027	0.1059	-0.0013	0.0052	0.250	0.0065	0.0026	0.1166	0.0033	0.0050	0.660
KRISS	0.0000	0.0025	0.1280	-0.0026	0.0047	0.553	0.0000	0.0023	0.1547	-0.0032	0.0042	0.762

Table 8-10. Comparison results for diffuser-type green LEDs after temperature correction.

lab	x						y					
	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n	Δ_i	$u(\Delta_i)$	w_i	D_i	$U(D_i)$	E_n
MIKES	0.0052	0.0070	0.0166	0.0022	0.0138	0.159	0.0018	0.0075	0.0165	-0.0012	0.0148	0.081
CMS-ITRI	0.0094	0.0104	0.0075	0.0064	0.0206	0.311	0.0055	0.0096	0.0101	0.0025	0.0191	0.131
PTB	0.0038	0.0028	0.1015	0.0008	0.0053	0.151	0.0022	0.0033	0.0871	-0.0009	0.0062	0.145
NMIJ	0.0048	0.0028	0.1011	0.0018	0.0054	0.333	-0.0011	0.0035	0.0775	-0.0041	0.0066	0.621
CENAM	0.0551	0.0038	N.A.	0.0521	0.0079	6.595	-0.1410	0.0086	N.A.	-0.1440	0.0174	8.276
LNE	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
METAS	0.0042	0.0034	0.0697	0.0012	0.0066	0.182	0.0032	0.0040	0.0589	0.0002	0.0077	0.026
NMC-A*STAR	-0.0007	0.0028	0.1034	-0.0037	0.0053	0.698	0.0126	0.0031	0.0976	0.0095	0.0058	1.638
NMIA	0.0006	0.0027	0.1005	-0.0024	0.0052	0.462	0.0014	0.0027	0.1185	-0.0017	0.0050	0.340
NIST	0.0034	0.0026	0.1118	0.0003	0.0049	0.061	0.0028	0.0029	0.1035	-0.0002	0.0055	0.036
VNIIOFI	0.0074	0.0030	0.0894	0.0044	0.0057	0.772	0.0012	0.0034	0.0807	-0.0019	0.0065	0.292
MKEH	0.0058	0.0036	0.0626	0.0028	0.0069	0.406	0.0035	0.0037	0.0671	0.0005	0.0072	0.069
INM	0.0028	0.0028	0.1067	-0.0002	0.0052	0.038	0.0059	0.0029	0.1079	0.0028	0.0055	0.509
KRISS	0.0000	0.0025	0.1291	-0.0030	0.0047	0.638	0.0000	0.0023	0.1746	-0.0030	0.0042	0.714

The comparison results for diffuser-type green LEDs without and with temperature correction are plotted in Fig. 8-7 and Fig. 8-8, respectively. The DoEs and its uncertainties

are plotted as dot symbols and error bars, respectively. The red lines indicate the expanded uncertainty of the comparison RV.

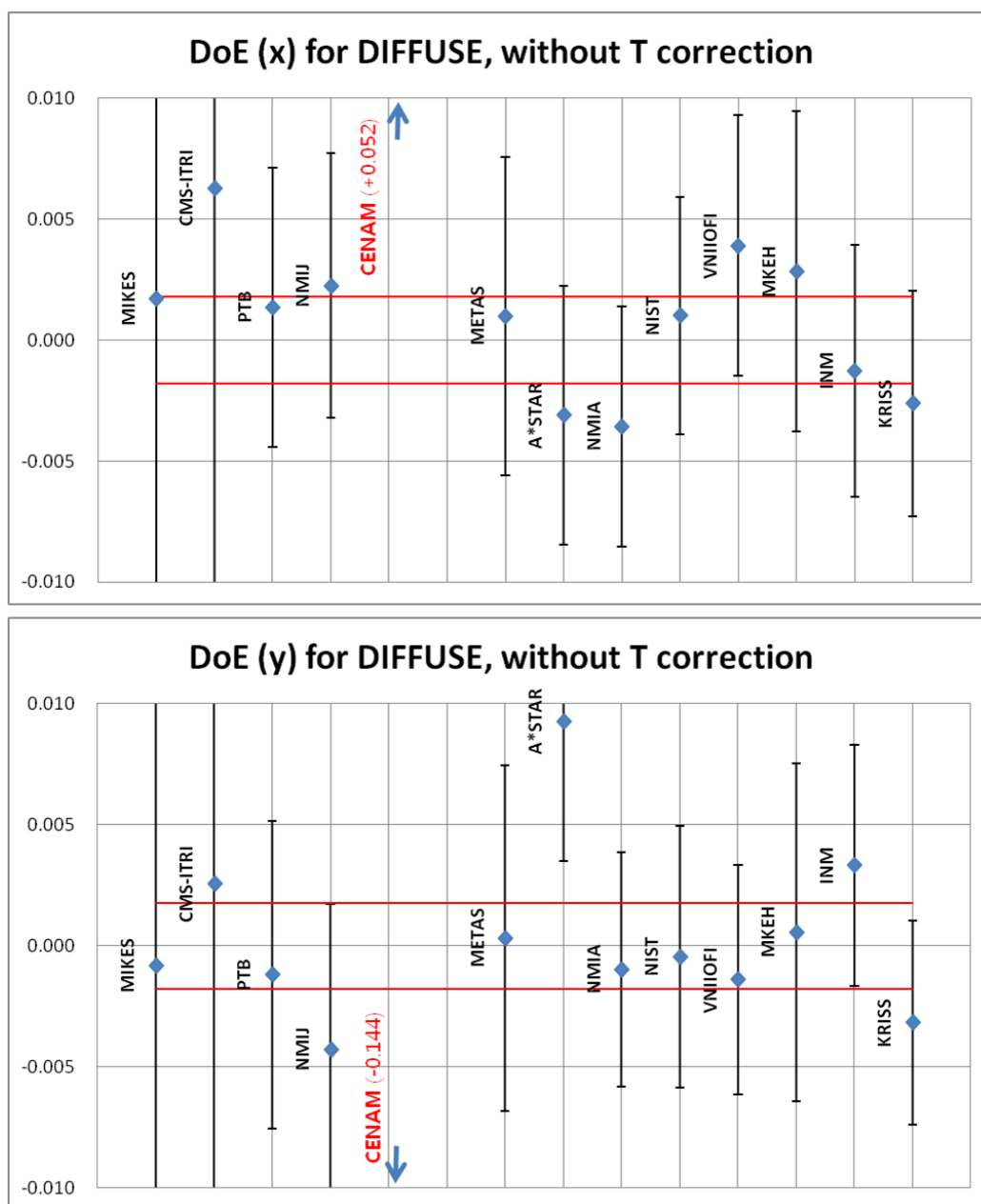


Fig. 8-9. DoE for diffuser-type green LEDs without temperature correction.

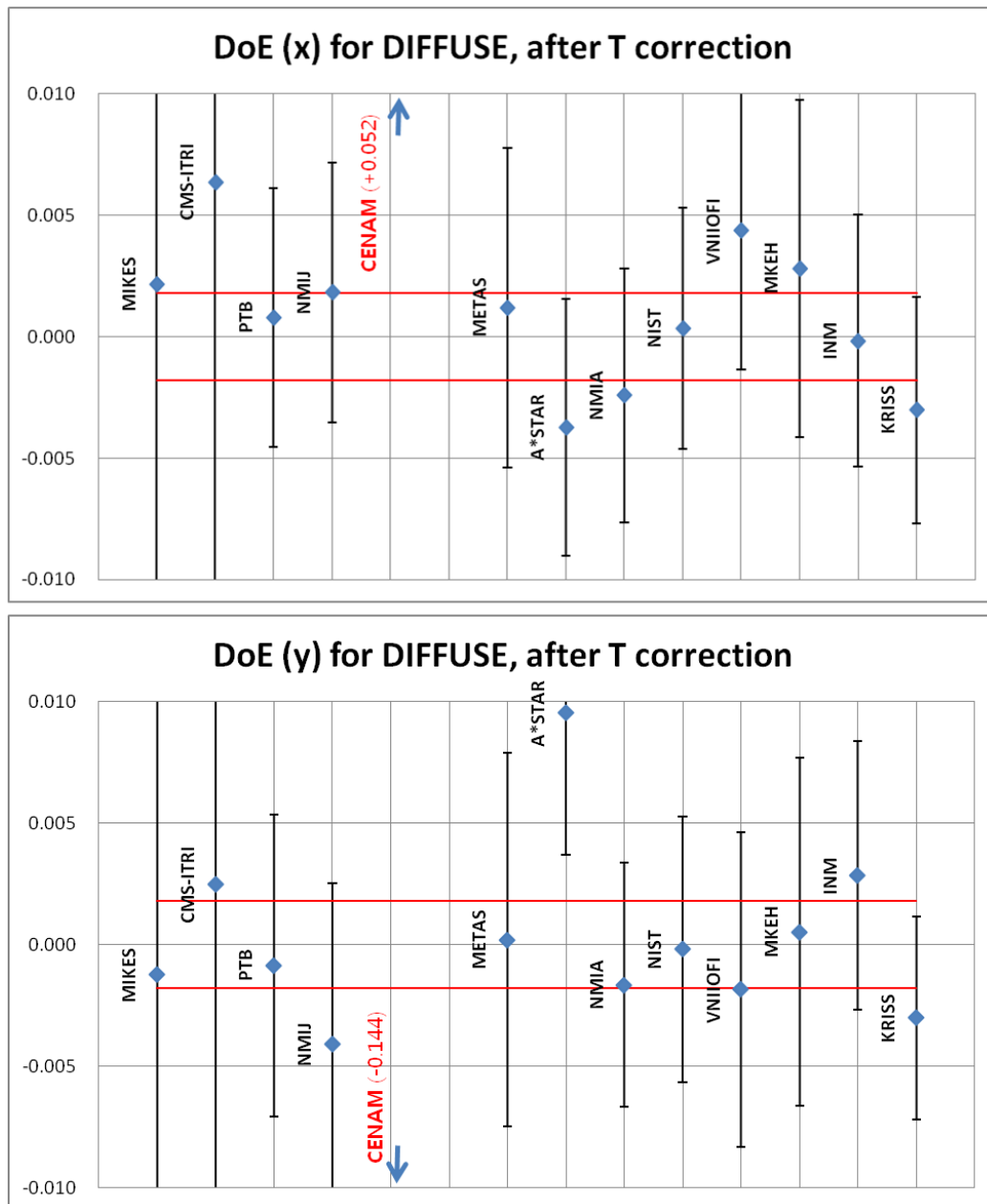


Fig. 8-10. DoE for diffuser-type green LEDs after temperature correction.

9. Discussion

9.1. Test of Consistency

In order to test the consistency of the comparison results, the Birge ratio R_B is calculated by the equation

$$R_B = \sqrt{\frac{1}{N} \sum_{i=0}^N \frac{\{A_i - A_{RV}\}^2}{u_{adj}^2(A_i)}}, \quad (9-1)$$

where N is the number of the participants, without counting the pilot, whose results are used for the calculation of the RV. For this calculation, the data of the outliers are not used. Note that the consistency is satisfied, if $R_B \leq 1$.

Table 9-1 shows the calculated Birge ratios of the comparison S3c without and with temperature correction. Many values of R_B are larger than 1, which indicate that the uncertainties of the participants are underestimated. Table 9-1 also shows that the temperature correction has the effect of decreasing the Birge ratios and, hence, improving the consistency. This verifies that the temperature correction based on the junction voltage measurement described in Chapter 3 is capable to correct the systematic errors of the artifact LEDs due to different measurement conditions.

Table 9-1. Birge ratio of the comparison S3c.

LED type	Birge ratio without T correction		Birge ratio after T correction	
	x	y	x	y
Red	1.574	0.694	1.484	0.691
Green	0.925	1.424	0.918	1.375
Blue	1.096	1.154	1.076	1.178
White	2.844	2.887	1.893	2.237
Diffuse green	0.868	1.183	0.841	1.149

10. Summary

The measurement of emitted color of LEDs in chromaticity coordinates CIE 1931 (x , y) is compared by circulating five different types of artifact LEDs (red, green, blue, white, and diffuser-type green) to 14 NMIs (including the pilot). The artifact LEDs are prepared by the functional seasoning to enable a temperature correction based on the junction voltage measurement. The comparison reference values and the unilateral degrees of equivalence (DoEs) of each participant are calculated for each type of LEDs from the reported measurement results. Table 10-1 and Table 10-2 show the summary of the DoEs and their uncertainties of each participant for each type of LEDs as the comparison result.

Table 10-1. Summary of the unilateral DoEs and their uncertainties for APMP.PR-S3c chromaticity coordinate x (temperature correction applied).

NMI	RED		GREEN		BLUE		WHITE		DIFFUSE	
	DoE (x)	U of DoE	DoE (x)	U of DoE	DoE (x)	U of DoE	DoE (x)	U of DoE	DoE (x)	U of DoE
MIKES	0.0011	0.0039	0.0005	0.0064	-0.0007	0.0022	0.0020	0.0110	0.0022	0.0138
CMS-ITRI	0.0001	0.0041	0.0042	0.0068	-0.0026	0.0036	0.0001	0.0068	0.0064	0.0206
PTB	0.0009	0.0033	0.0005	0.0064	-0.0002	0.0019	0.0005	0.0034	0.0008	0.0053
NMIJ	0.0009	0.0034	0.0000	0.0063	0.0000	0.0019	-0.0030	0.0048	0.0018	0.0054
CENAM	-0.1059	0.0136	0.0277	0.0059	0.0129	0.0033	0.0058	0.0026	0.0521	0.0079
LNE	0.0003	0.0077	-0.0007	0.0063	0.0000	0.0023	0.0002	0.0067	N.A.	N.A.
METAS	0.0013	0.0032	0.0011	0.0050	-0.0001	0.0018	-0.0003	0.0049	0.0012	0.0066
NMC-A*STAR	0.0014	0.0032	-0.0037	0.0054	-0.0009	0.0018	-0.0003	0.0030	-0.0037	0.0053
NMIA	-0.0091	0.0036	-0.0034	0.0053	0.0024	0.0019	-0.0061	0.0040	-0.0024	0.0052
NIST	0.0010	0.0032	-0.0001	0.0060	-0.0004	0.0018	0.0010	0.0027	0.0003	0.0049
VNIIOFI	0.0007	0.0036	0.0034	0.0053	-0.0018	0.0025	-0.0001	0.0028	0.0044	0.0057
MKEH	0.0006	0.0037	0.0040	0.0052	0.0005	0.0022	-0.0084	0.0047	0.0028	0.0069
INM	0.0015	0.0042	-0.0018	0.0054	-0.0006	0.0028	-0.0064	0.0054	-0.0002	0.0052
KRISS	-0.0007	0.0030	-0.0026	0.0047	0.0014	0.0017	0.0005	0.0013	-0.0030	0.0047

Table 10-2. Summary of the unilateral DoEs and their uncertainties for APMP.PR-S3c chromaticity coordinate y (temperature correction applied).

NMI	RED		GREEN		BLUE		WHITE		DIFFUSE	
	DoE (y)	U of DoE	DoE (y)	U of DoE	DoE (y)	U of DoE	DoE (y)	U of DoE	DoE (y)	U of DoE
MIKES	-0.0004	0.0017	0.0004	0.0047	0.0004	0.0042	0.0026	0.0165	-0.0012	0.0148
CMS-ITRI	0.0003	0.0046	0.0029	0.0073	0.0045	0.0060	0.0020	0.0065	0.0025	0.0191
PTB	-0.0002	0.0016	0.0000	0.0061	-0.0003	0.0040	0.0013	0.0037	-0.0009	0.0062
NMIJ	-0.0002	0.0015	0.0002	0.0052	0.0004	0.0041	-0.0013	0.0049	-0.0041	0.0066
CENAM	0.0088	0.0024	-0.0698	0.0083	0.0017	0.0049	-0.0093	0.0028	-0.1440	0.0174
LNE	0.0004	0.0033	-0.0009	0.0085	-0.0015	0.0053	0.0009	0.0095	N.A.	N.A.
METAS	-0.0005	0.0014	-0.0003	0.0045	0.0017	0.0038	0.0010	0.0054	0.0002	0.0077
NMC-A*STAR	-0.0005	0.0014	0.0087	0.0054	0.0007	0.0040	0.0015	0.0036	0.0095	0.0058
NMIA	0.0004	0.0016	-0.0072	0.0052	-0.0051	0.0037	-0.0038	0.0039	-0.0017	0.0050
NIST	-0.0001	0.0014	0.0006	0.0052	-0.0005	0.0037	0.0022	0.0025	-0.0002	0.0055
VNIOFI	-0.0004	0.0022	0.0005	0.0049	0.0036	0.0042	0.0025	0.0027	-0.0019	0.0065
MKEH	0.0002	0.0022	-0.0001	0.0046	0.0025	0.0040	-0.0033	0.0043	0.0005	0.0072
INM	-0.0012	0.0031	0.0026	0.0049	0.0000	0.0043	-0.0081	0.0058	0.0028	0.0055
KRISS	0.0013	0.0013	-0.0046	0.0043	-0.0031	0.0036	0.0020	0.0013	-0.0030	0.0042

Acknowledgement

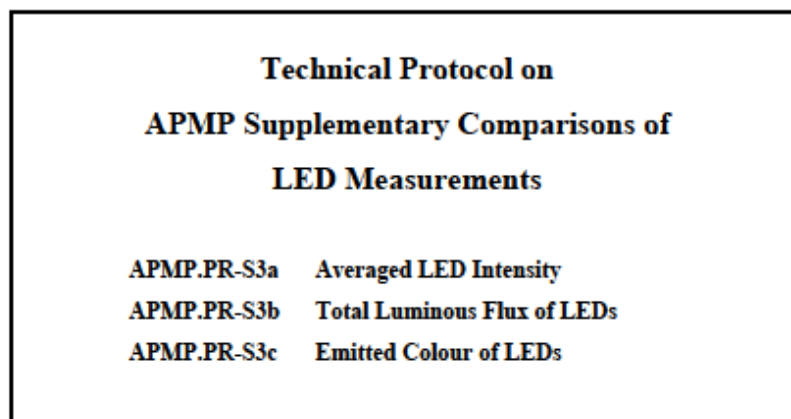
The pilot work of this comparison is partly supported by the Korean Ministry of Knowledge and Economy under the project of LED standardization, grant B0010209.

Appendix A: Technical Protocol

The pdf-file can be opened by a double-click on the image below.

AFMP supplementary comparison

1



Approved in January 2008, Revised in November 2008 due to change of participants list

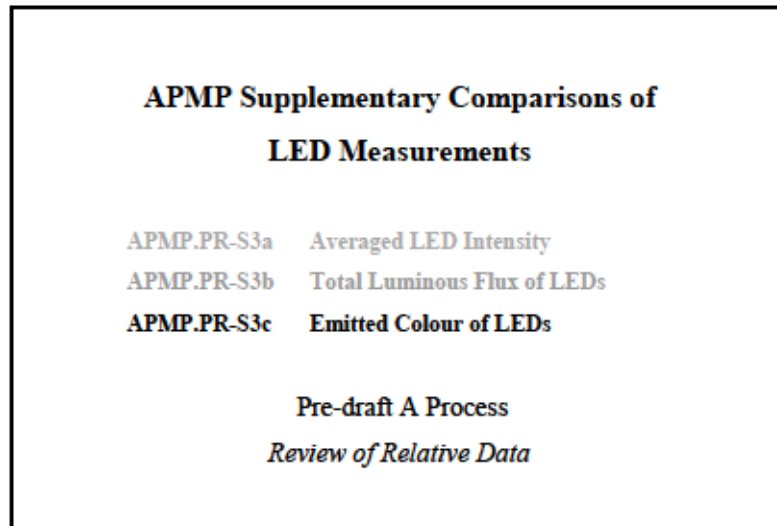
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Technical protocol on comparison of LED measurements

Appendix B: Review of Relative Data

The pdf-file can be opened by a double-click on the image below.



Appendix C: Comments from Review of Relative Data

The pdf-file can be opened by a double-click on the image below.

Summary of Comments in Review of Relative Data

VSL

Mail on Dec 14, 2009

Looking to the data of VSL we see a big instability for some of the LEDs. Can you tell me how you are going to deal with this and what the effect will be for the KCRV values or final presentation of the results?

Response of KRISS on Dec 22, 2009

I think the stability for the LEDs used for VSL is not so bad (all below 1 % drift). I propose to average the LEDs of the same type (three of red, three of green, etc.) and take the instability as an uncertainty component of the difference from the reference value. (There will be no KCRV and DoE because these are supplementary comparisons.)

Of course, we will exclude particular LEDs which show bad stability based on the opinion and agreement of the participant.

Mail on March 17, 2010

Looking to the remarks of the temperature correction data we are wondering if the inconsistency for some of the data has to do with the measurement of the junction voltage. As I can remember there was a relative large variation in voltage over the legs of the LEDs. So in some cases depending on the position of the junction measurement this can affect the correction for temperature. Of course one needs to take this variation into the uncertainty for the voltage measurement at the junction but maybe some of the inconsistencies can be explained looking to the uncertainty for junction measurements versus temperature correction and the variation of junction voltage over the legs of the LEDs.

Response of KRISS on March 24, 2010

It is true that there is a change of junction voltage when the measurement position of the LED electrodes changes. We have noticed this at the stage of the artefact preparation, and therefore arranged that this variation due to the junction position should be checked and reported by each participant as an uncertainty component of junction voltage.

Because we have all the sensitivity data of photometric quantity to junction voltage for each artefact LED, we can analyze the inconsistency caused by the inaccurate measurement of junction voltage. We will surely include this in the result report. From our experience, however, the uncertainty of photometric quantities propagated from the uncertainty of junction voltage measurement, including the junction position variation, was much lower than 0.5 %, which is the principal accuracy limit of the temperature correction method via junction voltage.

METAS

Mail on Dec 15, 2009

I have no special observation.

Mail on Feb 10, 2010

Appendix D: Comments from Review of Uncertainty Budgets

The pdf-file can be opened by a double-click on the image below.

Summary of Comments in Review of Uncertainty Budgets

Part 1. General Comments and Revisions

INM (Romania)

Mail on April 02, 2010

As far as the INM reports are concerned, the uncertainty budgets for Green, Blue, White and Diffuse LEDs were not included in the APMP PR S 3a and APMP PR S3b reports just because they are very close to our uncertainty budgets for the Red LEDs so we thought not necessary to repeat the almost exactly same figures. But do you think this is necessary or should we merely mention this in the reports? Anyway, in order to comply I'll revise and sent you our reports today, provided it's not already too late.

Here attached are our revised reports for APMP PR S3a and APMP PR S3b comparisons, including the uncertainty budgets for all types of LEDs.

Please notice that changes only concerned the spectral correction factors for the various LEDs and while the combined standard uncertainties were of about 5.5 %, the various spectral correction factors induced quite small changes (less than ± 0.5 %) in the combined uncertainties values. That's why, initially we only reported the uncertainty budgets for the red LEDs.

Response of KRISS on April 12, 2010

I have properly received your two documents including the uncertainty budgets for all color-types of LEDs. The formats you sent me are ok.

Because your revision deals only with an addition of information, I see no problem to accept your revision for the report. I will wait for a while for other revisions or corrections, and distribute the revised files then.

METAS

Mail on April 15, 2010

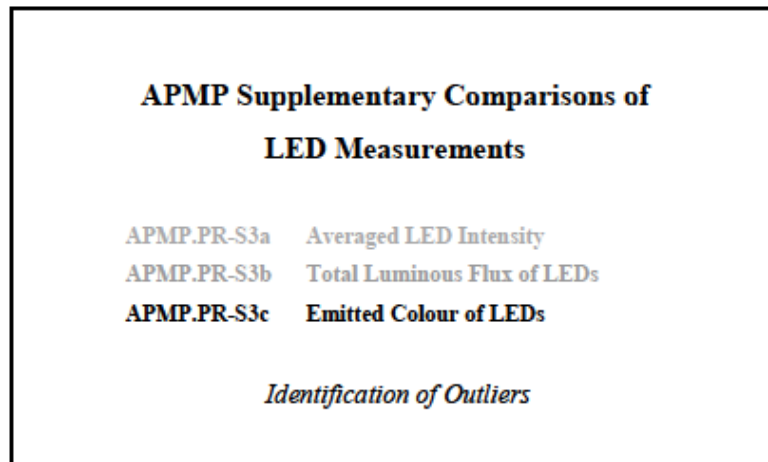
Please find enclosed an update of our description of the uncertainty budget of the chromaticity coordinates. I'm sorry to have it sent after your deadline. In the updated version I stated explicitly uncertainty budgets for the 4 types of LEDs. It's just to give more information, no value has been changed.

I also would like to recall our worries in respect to the correlation of chromaticity coordinates (see the attached file).

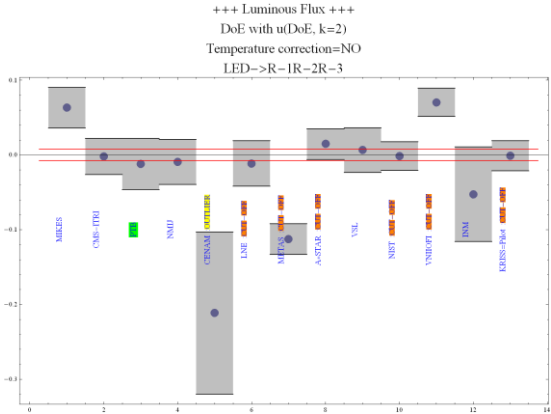

APMP:PR-S3
Correlation of chrc

Appendix E: Identification of Outliers

The pdf-file can be opened by a double-click on the image below.



Appendix F: Comments and Revision to Draft A Report

Comments from PTB to Data Analysis Results on 11 April 2011	Replies by the pilot on 17 June 2011
Enclosed please find copies of your files with some marked blue cells. We think there are some small bugs.	I have checked them and corrected. Thank you!
It is possible to refer this comparison to KCRV using link laboratories.	In principle yes. But the related KC, e.g. of luminous flux, was done with a different artifact so that it cannot be directly compared to this LED comparison. That is also the reason why this is a supplementary comparison. We can try to do such a linkage as an interesting study, but not as a part of the comparison report.
The resulting excel graphic looks a little bit strange. We feel it should look similar like the following graphic (uDoE should be plotted around DoE):	I agree and I checked that this is also common for KCs. I will modify the graphs as you suggest.
	It may be helpful to calculate the Birge ratio to get information about the consistency of the comparisons. It is calculated from the internal and external This is a good suggestion. I will surely try to calculate both the Birge ratio and the En values and include the results in the final report. This will provide valuable

consistency. A value of close to 1 or less indicates that the results are consistent. Values greater than 1 are not.

$$R_B = \frac{u_{\text{ext}}}{u_{\text{in}}} \quad \text{with}$$

$$u_{\text{ext}} = \sqrt{\frac{\sum_{i=1}^n [D_i / u(D_i)]^2}{(n-1) \sum_{i=1}^n u^{-2}(D_i)}} \quad \text{and}$$

$$u_{\text{in}} = \left(\sum_{i=1}^n u^{-2}(D_i) \right)^{-1/2}.$$

For luminous flux we found values around 2 for most cases. For luminous intensity (without diffuse LEDs) we found values around 1. Please see enclosed jpg files (I apologize this jpg, but it takes a while to get nice prints with mathematica). We also calculated the criteria by

$$E_{n,i} = \text{Abs} \left(\frac{DoE_i}{2u(DoE_i)} \right)$$

Values greater than 1 indicate a too small uncertainty of the participant. So we suggest to use specific enlargements of the participant uncertainties in that way that the Birge ratio is equal or less 1 and criteria is close to 1. This procedure also would solve the problem of outliers.

information to the next version of the KC guidelines which should include a procedure of consistency check and of a better outlier selection.

Comments from PTB to Draft A Report on 19 Oct 2011

We found some typing errors in the draft A paper. Enclosed please find our errata ZIP-file.

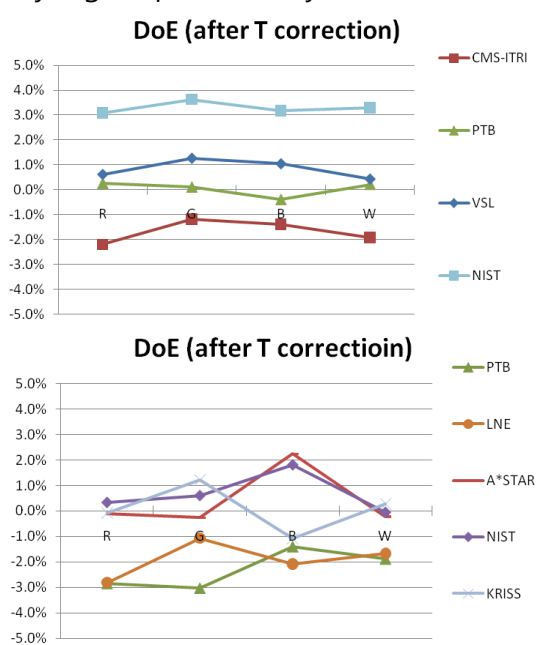
Replies by the pilot on 22 Nov 2011

I have checked the errors. But all the errors you found were the corrections of the uncertainty budgets of PTB. These, however, cannot be corrected in the draft A report stage, because they are already

	reviewed by the participants. This is communicated via email on 21.10.2011. PTB has acknowledged this and confirms that these corrections do not affect the comparison results. Therefore, the corrections are not considered in the revision of the draft A report.
The Plots Fig. 9-1 of S3a and S3b are very helpful. It would be great to have these plots for S3c, too.	In case of S3c, the plots such as Fig. 9-1 of S3a and S3b were not easy because a 2 dimensional plot is required to make systematic effects visible. I will try to realize this in the next revision of the S3c report, but I should also manage the workload. Based on the results data, however, each participant can make such analysis to investigate the systematic effect of his results.
The appendices should include all important comments, suggestions and recommendations of the participants to simplify future comparisons. For example our Suggestions PTB.docx of 15.04.2011.	I will make another appendix to record the comments during the draft A report procedure.
The tables in chapter 8 should include the criteria $E_{n,i} = \text{Abs}\left(\frac{DoE_i}{2u(DoE_i)}\right)$ that would be helpful to evaluate the stated uncertainty by each participants.	I will consider this in the revision.
The Birge ratios stated in table 9-1 especially for S3a and S3a are often significant greater than 1. I think the	I agree that the large Birge ratio means that the uncertainties of the participants are underestimated. I wrote this also in the

meaning of that is, that some stated uncertainties are too small. Please, refer the related En criteria.

Here we have an additional hint for that. The first diagram from S3a (intensity) shows a relative flat DoE around 0% of PTB results. But the second diagram from S3b (flux) shows relative big differences between (R,G) and (B,W) LEDs. The luminous flux values were determined by a goniophotometer directly after the luminous intensity measurement with the same operation state of the LED and in the same system without new alignment of the LED. So there is no reason for that difference. We know from hundreds of measurements that the integration capability of the goniophotometer has a very high reproducibility.



So I think this a hint for an inconsistency of the data as we know from the Birge ratios.

report. Your statement will be documented in the Appendix of the revised report.

List of Revisions from A-1 to A-2

Draft A-1	Draft A-2
Chapter 8, the first paragraph of each section.	Addition of a sentence "The last columns of each table Table 8-2 shows the E_n criteria of each participant, which is defined as the absolute ratio of D_i and $U(D_i)$."
Chapter 8, Table 8-1 ~ Table 8-10.	Addition of new columns with the calculated E_n criteria values.
After Appendix E	Addition of <Appendix F: Comments and Revision to Draft A Report>