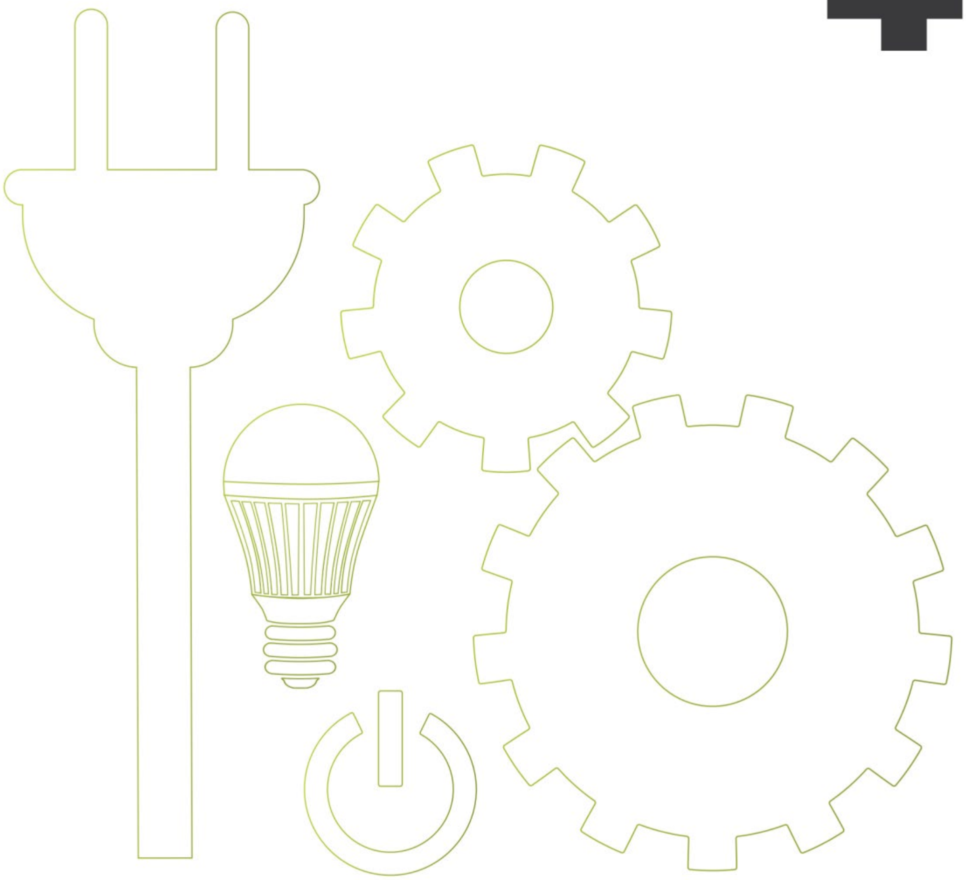
Energy Efficient End-use Equipment
International Energy Agency



Solid State Lighting Annex: IC 2017 Nucleus Laboratory Comparison Report

Final Draft

Energy Efficient End-Use Equipment (4E)
International Energy Agency

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IEA 4E Solid State Lighting Annex
Interlaboratory Comparison 2017 (IC 2017)
Nucleus Laboratory Comparison Report

Authors:

Yoshi Ohno, Ph. D., SSL Annex IC 2017 Task Leader, National Institute of Standards and Technology, USA

Jun Seok Oh, SSL Annex IC 2017 Nucleus Laboratory Expert, Korea Institute of Lighting Technology (KILT), Republic of Korea

Sangkyoo Jeon, Ph. D., SSL Annex IC 2017 Organizing Laboratory Leader, Korea Institute of Lighting Technology (KILT), Republic of Korea

Jean Gaudemer, SSL Annex IC 2017 Nucleus Laboratory Expert, Laboratoire National de Métrologie et d'Essais (LNE), France

Jimmy Dubard, Ph. D., SSL Annex IC 2017 Nucleus Laboratory Leader, Laboratoire National de Métrologie et d'Essais (LNE), France

Errata note:

It was brought to our attention that that Power Factor had been omitted from Table 7 1., SDPA Values for IC 2017. This has now been added in this revised version, dated 28 May 2019, rev. 30 September 2019.

About the IEA 4E Solid State Lighting Annex: The SSL Annex was established in 2010 under the framework of the International Energy Agency's Energy Efficient End-use Equipment (4E) Implementing Agreement to provide advice to its member countries seeking to implement quality assurance programmes for SSL lighting. This international collaboration currently consists of the governments of Australia, Canada, Denmark, France, the Republic of Korea, Sweden and the United Kingdom. Information on the 4E SSL Annex is available from: http://ssl.iea-4e.org/

The Energy Efficient End-Use Equipment (4E) Technology Collaboration Programme was established by the International Energy Agency (IEA) in 2008 to support governments in coordinating effective energy efficiency policies. Twelve countries have joined together under the 4E platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However 4E is more than a forum for sharing information – it pools resources and expertise on a wide a range of projects designed to meet the policy needs of participating governments. Participants find that is not only an efficient use of available funds, but results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions. Current members of 4E are: Australia, Austria, Canada, China, Denmark, France, Japan, Korea, Netherlands, Switzerland, Sweden, the United Kingdom and the United States of America. Further information on the 4E Implementing Agreement is available from: www.iea-4e.org

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Foreword

This report is an important milestone in the IEA 4E SSL Annex's 2017 Interlaboratory Comparison (IC 2017). It is part of the quality assurance process of IC 2017. It serves as the link between the two Nucleus Laboratories and the individual participant laboratories' test results by establishing equivalence between the measurements of the two nucleus labs – KILT in Korea and LNE in France.

The report demonstrates that these two laboratories are equivalent for the measurement of the samples tested. The report provides detail on labs, the sample tested, the procedure followed, the results measured, the calculation of correction factors and the comparison.

Participant laboratories in IC 2017 have been assigned to one of our two nucleus laboratories for comparison of their results. This report establishes that any participant's results can be compared to those of any other participant in IC 2017, regardless of which of the two nucleus laboratories they were assigned to.

Following the publication of this report, IC 2017 participant reports will be issued. Following that process, we can all look forward to a very exciting comparison and analysis of 43 goniophotometers in 37 laboratories in 18 countries. A comparison of goniophotometers at this scale has never been done before, and we are excited about what lies ahead.

Nils Borg
Operating Agent
IEA 4E SSL Annex

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Acronyms and Abbreviations

AC	alternating current
4E	Energy Efficient End-use Equipment
ART	artefact
°C	degrees Celsius
CCT	correlated colour temperature
CIE	Commission Internationale de l'Éclairage (International Commission on Illumination)
CRI	colour rendering index
DC	direct current
DUT	device under test
Hz	hertz
IC	Interlaboratory Comparison
IEA	International Energy Agency
IEC	International Electrotechnical Commission
K	Kelvin
kg	kilograms
KILT	Korea Institute of Lighting Technology
LED	light emitting diode
lm	lumen
LNE	Laboratoire National de métrologie et d'Essais
min	minutes
mm	millimetre
MR	multifaceted reflector
NIST	National Institute of Standards and Technology
nm	nanometre
RMS	root mean square
SPD	spectral power distribution
SSL	solid state lighting
TSRF	total spectral radiant flux
V	volts
W	watt

1 Introduction

The IEA 4E SSL Annex launched an Interlaboratory Comparison in 2017 (IC 2017) to support the measurement of SSL products by goniophotometers around the world. IC 2017 is being organised to compare measurements of LED luminaires (including roadway lighting, a planar luminaire, and a batten) and a narrow-beam angle LED lamp. None of these products or type of products were covered in the SSL Annex's previous Interlaboratory Comparison in 2013 (IC 2013). This new interlaboratory comparison, IC 2017, is investigating the measurement variations and the capabilities of participating laboratories using goniophotometers to measure SSL products. It is also studying the equivalence of measurements by different types of goniophotometers, e.g. the traditional far-field types and the newer camera based near-field goniophotometers.

IC 2017 is being led by the National Institute of Standards and Technology (NIST), USA. Measurement rounds of IC 2017 will be carried out by two Nucleus Laboratories, Korea Institute of Lighting Technology (KILT), Korea, and Laboratoire national de métrologie et d'essais (LNE), France. To verify their measurement uncertainties and to bring equivalence of their measurements of the IC 2017 artefacts, comparisons between the Nucleus Laboratories were carried out. Based on the results of this comparison, the correction factors for equivalence of measurements by the two Nucleus Laboratories as prescribed in IC 2017 Technical Protocol [1] were determined. In addition, the primary scales of total spectral radiant flux of the two Nucleus Laboratories were compared with measurements at NIST.

Unfortunately, the goniophotometer at KILT experienced a problem and had to be repaired during the measurement rounds. There were small effects on KILT's measurement results, which were corrected in most cases, but some measurements had to be repeated. To ensure accurate results, all measurements for the Nucleus Laboratory comparison were repeated after the goniophotometer was repaired, the results of which are given in this Report.

2 Protocol of Nucleus Laboratory Comparison

This Nucleus Laboratory comparison followed the IC 2017 Technical Protocol [1] published in June 2017.

2.1 Comparison Artefacts

Two full sets of comparison artefacts (ART-1, ART-2, ART-3, ART-4) described in the IC 2017 Technical Protocol were used in this Nucleus Laboratory comparison. These two artefact sets are referred to as Set #1 and Set #2. The characteristics of these artefact sets are listed in Table 2-1. ART-1 is operated on DC 12 volts (V), and other artefacts are operated on AC 220 V, 60 Hertz (Hz). Further details of these artefacts are described in the IC 2017 Technical Protocol [1]. KILT prepared the artefacts by seasoning them for 200 hours and testing for reproducibility, then they were measured by KILT (first measurement, noted as

"Before") and shipped to LNE. LNE measured the artefacts and shipped them back to KILT for a second measurement at KILT (noted as "After").

Table 2-1. Specifications of the Comparison Artefacts

Designation Type	Picture (actual)	Size	Rated voltage, Power, nominal CCT	Other
ART-1: Narrow-beam lamp		MR-16 50mm x 45mm	12V DC 7.5 W 2700K	Narrow beam angle < 20°
ART-2: Planar luminaire		615mm x 615mm x 15 mm	220V AC, 60 Hz 40W 5700K	Broad (near Lambertian) distribution
ART-3: Batten luminaire		625mm x 56mm x 85mm diffuse cover	220V AC, 60 Hz 20W 4000K	Broad distribution with small upward emission
ART-4: Street lighting luminaire		500mm x 251mm x 105mm 5.5 kg	220V AC, 60 Hz 4000K 20W	Asymmetric beam emission pattern

2.2 Measurement Quantities

All measurement quantities listed in Tables 2 and 3 of IC 2017 Technical Protocol [1] were measured by the two Nucleus Laboratories. These are:

- Total luminous flux
- Luminous efficacy
- Active power
- RMS current
- Power factor
- Chromaticity coordinates (u', v')
- Correlated colour temperature (CCT)
- Colour Rendering Index (CRI) R_a
- Luminous intensity distribution
- Partial luminous flux (measured for ART-1 only)
- Street light partial flux (measured for ART-4 only)
- Beam angle
- Centre beam intensity
- Angular colour uniformity (measured for ART-1 and ART-3)

3 Measurement Instruments used by Nucleus Laboratories

3.1 Measurement of luminous flux and luminous intensity distribution

Both Nucleus Laboratories used a goniophotometer with a photometer head (which allows fast scanning) for measurements of luminous flux and luminous intensity distribution. LNE applied a spectral mismatch correction to each device under test (DUT) with its spectral power distribution (SPD) measured using a sphere-spectroradiometer system. KILT uses a photometer head with f_1'=1.2 % (meeting CIE S 025 requirement) and thus no spectral mismatch correction was applied at KILT.

3.2 Measurement of colour quantities

In IC 2017, measurements of artefacts will be made primarily using goniophotometers. However, the use of sphere-spectroradiometers (integrating sphere with a spectroradiometer) will be permitted for measurements of (spatially-averaged) colour quantities because this is common practice in testing laboratories measuring LED luminaires. In the IC 2017 Technical Protocol, (spatially-averaged) colour quantities can be measured either by (1) using gonio-spectroradiometer and calculating spatially averaged values or (2) using a sphere-spectroradiometer. This same option for measuring colour quantities was offered to the Nucleus laboratories, and they decided which instruments they would use. Both KILT and LNE chose to use their sphere-spectroradiometer for (spatially averaged) colour quantities, however angular colour uniformity was measured with a gonio-spectroradiometer (i.e., a goniophotometer with a spectroradiometer).

3.3 Instruments used by KILT

The specifications of instruments used by KILT are listed in Table 3-1 and Table 3-2, and a photo of their goniophotometer is shown in Figure 3-1. The construction of KILT's goniophotometer is such that the mirror rotates vertically around the DUT which is mounted at the centre of rotation of the mirror. The DUT is at a fixed position and rotates horizontally around it's optical axis. The mirror rotates over 180° covering a half vertical plane, thus the DUT rotates 360° horizontally with rotation axis toward direction of gravity. The measurement is taken in on-the-fly mode for the photometer head. Measurement with a spectroradiometer is taken in stop-and-go mode.

Table 3-1. Information of the Goniophotometer used by KILT

Aspect / Equipment	Characteristic / Value
Goniophotometer Manufacturer/Model	PSI / LG-2.0
Type of Goniophotometer	Light source is at rotation centre, and mirror rotates around the light source
Operating position of DUT	Fixed (rotation axis of light source is in the direction of gravity
Photometric distance for photometer head	12.05 m
Photometric distance for spectroradiometer	12.05 m
Photometer head f1' (including mirror)	1.23 %
Spectroradiometer (for colour uniformity only)	PSI LG-2.0
γ angle scanning range	0° to 180°
Traceability of luminous intensity and luminous flux (goniophotometer)	Total spectral radiant flux standards traceable to NIST (Everfine Certificate No. C201410200505, No. C201410200506) (for IC 2017)
Traceability of goniospectroradiometer mode (colour uniformity only)	Total spectral radiant flux standards traceable to NIST (for IC 2017)
AC power supply used	EXTECH 6920
AC power meter used	Yokogawa WT210
Voltage measurement	At the DUT and 4-wire connection to instruments
Length of cable between DUT and power supply/power meter	7 metres

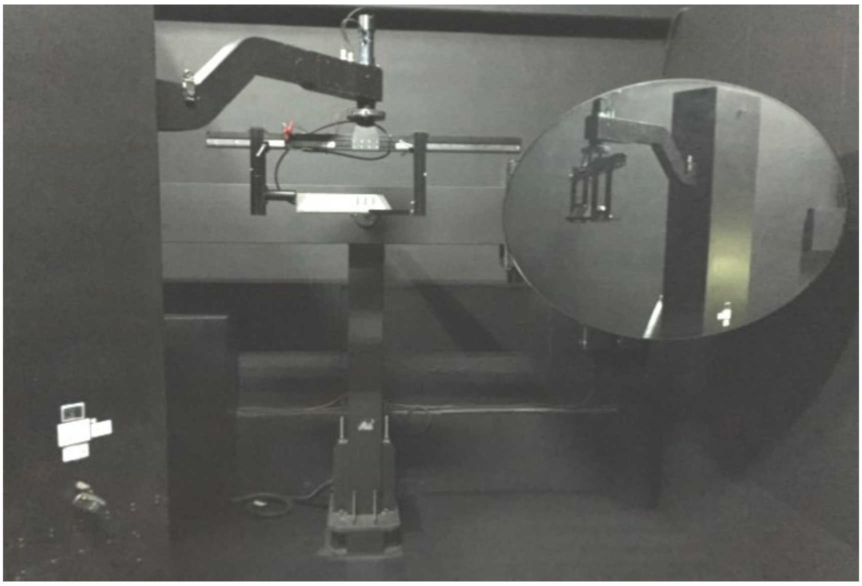


Figure 3-1. A photo of the goniophotometer at KILT, with ART-4 sample mounted

Table 3-2. Information of the Sphere-Spectroradiometer system used by KILT

Aspect / Equipment	Characteristic / Value
Diameter of integrating sphere	2 m
Spectroradiometer	Array-spectroradiometer (Everfine Model HASS/2000)
Wavelength range	350 nm to 830 nm
Bandwidth of spectroradiometer	2.0 nm
Wavelength interval	1 nm
Traceability	Total spectral radiant flux standard lamps traceable to NIST (Everfine Certificate No. C201410200505, No. C201410200506)
AC power supply used	Everfine DPS2010_V100
AC power meter used	Everfine PF2010
Voltage measurement	At the DUT and 4-wire connection to instruments
Length of cable between sphere and power supply/power meter	3 metres

3.4 Instruments used by LNE

The specifications of instruments used by LNE are listed in Table 3-3 and Table 3-4, and a photo of their goniophotometer is shown in Figure 3-2.

Table 3-3. Information of Goniophotometer used by LNE

Aspect / Equipment	Characteristic / Value
Goniophotometer Manufacturer/Model	Built by LNE
Type of Goniophotometer	Light source is at rotation centre, and mirror rotates around the light source
Operating position of DUT	Fixed (rotation axis of light source is in the direction of gravity
Photometric distance for photometer head	25 m
Photometric distance for spectroradiometer	6 m
Photometer head f1' (including mirror)	4.9 % (spectral mismatch correction applied)
Spectroradiometer (for colour uniformity only)	Array-spectroradiometer (QE Pro QEP01419)
γ angle scanning range	0° to 160°
Traceability of luminous intensity and luminous flux (goniophotometer)	Total luminous flux scale realized by LNE (BIPM Key Comparison Database, Appendix C [3])
Traceability of goniospectroradiometer mode	Spectral irradiance scale realized by LNE (BIPM Key Comparison Database, Appendix C [3])
AC power supply used	ELGAR 1251
AC power meter used	Yokogawa WT210
Voltage measurement	At the DUT and 4-wire connection to instruments
Length of cable between goniophotometer and power supply/power meter	10 m

The construction of LNE's goniophotometer is such that the DUT is mounted at the end of a rotating arm, and rotates vertically around the mirror in the centre, keeping its burning position constant with respect to gravity. The mirror rotates around itself synchronized with rotation of DUT so that its optical axis to the detector is a fixed line. The DUT also rotates horizontally around its optical axis. The vertical movement (rotation) of the DUT is 360° so that DUT's horizontal rotation is over 180°. The measurement is taken in on-the-fly mode for both the photometer head and the spectroradiometer. The dead angle (160° to 180° in angle) did not affect measurements for the artefacts of this comparison, except there were insignificant errors in total luminous flux of ART-3 luminaire; which were negligible. Also, in the measurement of the halogen standard lamps for total spectral radiant flux, this dead angle was shadowed by the base of the lamp so there were no effects.

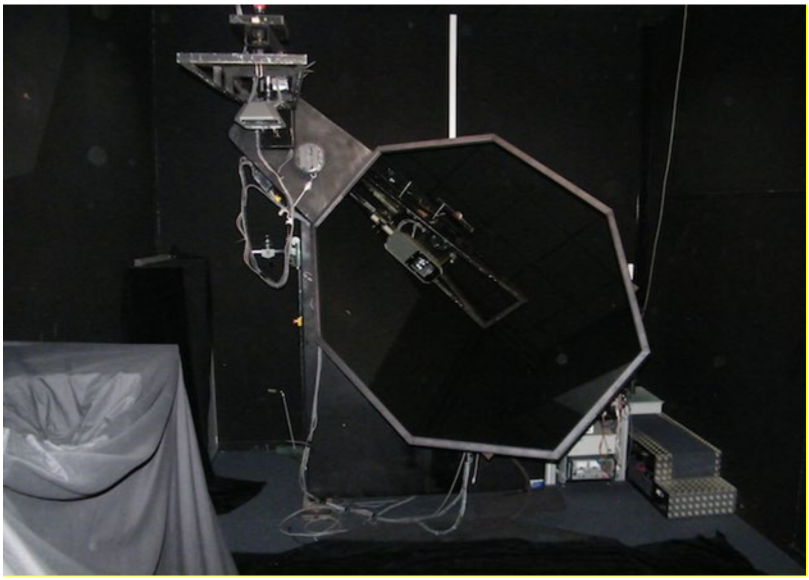


Figure 3-2. A photo of the goniophotometer at LNE, with ART-4 sample mounted

Table 3-4. Information of the Sphere-Spectroradiometer system used by LNE

Aspect / Equipment	Characteristic / Value
Diameter of integrating sphere	2 m
Spectroradiometer	Array-spectroradiometer (QE Pro QEP01419)
Wavelength range	350 nm to 1100 nm
Bandwidth of spectroradiometer	1.5 nm
Wavelength interval	0.8 nm
Traceability	Total spectral radiant flux scale realized by LNE
AC power supply used	ELGAR CW801
AC power meter used	Yokogawa WT210
Voltage measurement	At the DUT and 4-wire connection to instruments
Length of cable between sphere and power supply/power meter	10 m

4 Comparison of Total Spectral Radiant Flux

In addition to comparing LED lighting artefacts, two total spectral radiant flux (TSRF) standard lamps (100 W tungsten halogen lamps) were measured by KILT and LNE to compare their primary scales. The lamps were previously calibrated by NIST and then shipped from KILT to LNE and back to KILT. The measurements were made with their sphere-spectroradiometer systems against each lab's total spectral radiant flux standards, to which both their sphere system and goniophotometer are traceable. This comparison verified their luminous flux scale and colour measurements compared to the NIST scale, using stable incandescent standard lamps. The results are shown in Table 4-1.

Table 4-1. Summary Results of Total Spectral Radiant Flux Measurements

Metric Measured	NIST			KILT (Before)			LNE			KILT (after)		
	Lamp 1	Lamp 2	*U* (k=2)	Lamp 1	Lamp 2	*U* (k=2)	Lamp 1	Lamp 2	*U* (k=2)	Lamp 1	Lamp 2	*U* (k=2)
Lum. Flux (lm)	2295.4	2316.4	0.80%	2283	2290.7	1.5%	2305.3	2324.3	1.3%	2309.4	2310.2	1.5%
u'	0.2468	0.2468	0.0004	0.2471	0.2471	0.0005	0.24637	0.2465	0.0006	0.24701	0.2470	0.0005
v'	0.5195	0.5195	0.0003	0.5197	0.5198	0.0004	0.51911	0.5192	0.0004	0.51964	0.5197	0.0004
CCT (K)	3109	3109	10	3100	3099	14	3122	3118	17	3102	3101	14
	U(k=2) of comparison			KILT (Before) - NIST			LNE - NIST			KILT (After) - NIST		
$\Delta\Phi$ (%)	1.0%	1.0%		-0.53%	-1.11%		0.43%	0.34%		0.61%	-0.27%	
$\Delta u'$	0.0003	0.0003		0.0003	0.0003		-0.0004	-0.0002		0.0002	0.0003	
$\Delta v'$	0.0003	0.0003		0.0002	0.0003		-0.0004	-0.0003		0.0001	0.0002	
ΔT (K)	5	5		-9	-11		14	9		-7	-9	

These results showed good agreement overall among the three labs. NIST results lie between KILT and LNE. It was verified that both labs' primary scales of luminous flux were in good agreement with NIST within about 1%, and their primary scales for colour quantities (relative spectral radiant flux) were also in agreement within their stated uncertainties.

5 Characterisation of the Artefacts

A representative set of artefacts was tested for ambient temperature sensitivity and input voltage sensitivity. The results are presented in Table 5-1 and Table 5-2, respectively. Ambient temperature sensitivity was measured by changing the air temperature inside an integrating sphere. Each artefact was measured at an ambient temperature of approximately 25°C and at 30°C and measurements were taken after each artefact had stabilised. Input voltage sensitivity was measured while the artefact was operated in the sphere by adjusting the input voltage by about 1% and then taking measurements after two minutes.

Table 5-1. Ambient Temperature Sensitivity of the Artefacts (change /°C)

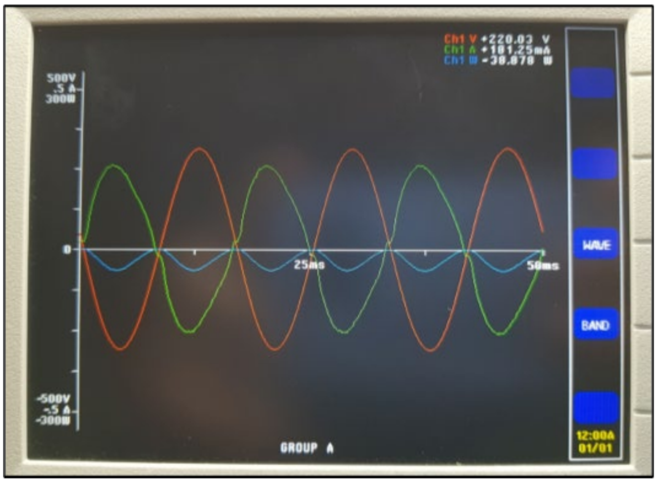
Parameter Measured	ART-1 Narrow beam lamp	ART-2 Planar Luminaire	ART-3 Batten Luminaire	ART-4 Street Light Luminaire
Current	-0.01%	-0.11%	-0.61%	-0.01%
Active power	-0.01%	-0.11%	-0.65%	0.00%
Power factor	-	0.0000	0.0000	0.0000
Luminous flux	-0.18%	-0.34%	-0.83%	-0.07%
Luminous efficacy	-0.17%	-0.23%	-0.19%	-0.07%
chromaticity *u*'	0.0000	0.0000	0.0000	0.0000
chromaticity *v*'	0.0001	-0.0000	-0.0002	-0.0000
CCT (unit: K)	-0.8	0.9	1.9	0.0

Table 5-2. Input Voltage Sensitivity of Artefacts (change / % change in voltage)

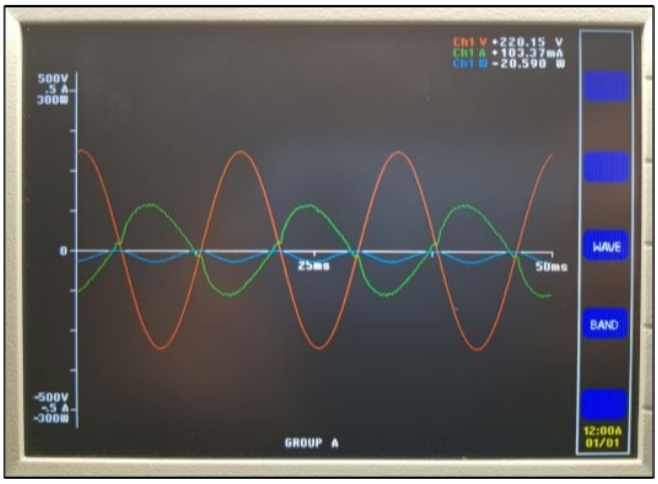
Parameter Measured	ART-1 Narrow beam lamp	ART-2 Planar Luminaire	ART-3 Batten Luminaire	ART-4 Street Light Luminaire
Current	-1.28%	-1.23%	-0.72%	0.05%
Active power	-0.26%	0.03%	0.00%	0.03%
Power factor	-	0.0000	0.0000	0.0000
Luminous flux	0.09%	0.24%	-0.01%	0.07%
Luminous efficacy	0.35%	0.21%	-0.01%	0.04%
chromaticity *u*'	-0.0001	0.0005	0.0000	0.0000
chromaticity *v*'	0.0000	0.0001	0.0002	0.0000
CCT (unit: K)	2.0	-32.0	0.0	-2.0

The electrical waveforms of the AC voltage artefacts (ART-2, ART-3, ART-4) were measured and are shown in Figure 1. There were no sharp or spiky current waveforms observed in any of the artefacts, though some distortions were observed.

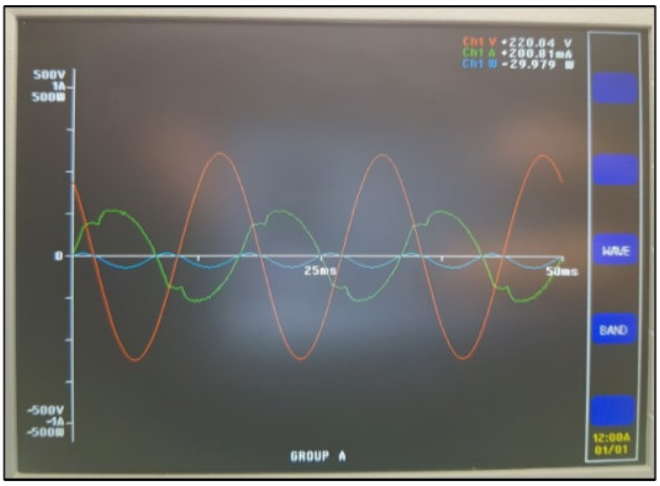
ART-2



ART-3



ART-4



Red curve is voltage

Green curve is current (phase reversed)

Blue curve is active power

Figure 5-1. Electrical waveforms of the AC-operating artefacts (ART-2, ART-3, ART-4)

6 Results

6.1 Operating Conditions

Table 6-1 and Table 6-2 present the typical operating conditions under which the Nucleus Laboratories took measurements of the two artefact sets. Each artefact was measured two times on each occasion. The data of only the first measurements are shown, and the KILT data of only before shipping the artefacts to LNE (KILT-Before) are shown, as examples. Conditions for the 2nd measurements and KILT-After measurements were similar to the values in these tables.

Table 6-1. Operating Conditions for Measurements of Artefact Set #1, LNE and KILT-Before

KILT	units	ART-1	ART-2	ART-3	ART-4	*U* (k=2)
Ambient temperature (goniophotometer)	°C	25.8	25.6	25.0	24.9	0.7
Ambient temperature (sphere system)	°C	25.1	24.8	24.6	25.3	0.7
Supply voltage measured (V)	V	12.03	220.25	220.25	220.14	0.22%
Stabilization time (min)	min	60	60	60	70	
LNE						
Ambient temperature (goniophotometer)	°C	25.3	25.7	25.5	24.8	0.7
Ambient temperature (sphere system)	°C	24	26.2	24.3	26.2	0.7
Supply voltage measured (V)	V	12.01	220.06	220.07	219.98	0.10%
Stabilization time (min)	min	90	90	90	90	

Table 6-2. Operating Conditions for Measurements of Artefact Set #2, LNE and KILT-Before

KILT	units	ART-1	ART-2	ART-3	ART-4	U (k=2)
Ambient temperature (goniophotometer)	°C	25.9	25.8	24.8	25.0	0.7
Ambient temperature (sphere system)	°C	24.6	24.7	24.9	25	0.7
Supply voltage measured (V)	V	12.04	220.04	220.16	220.15	0.22%
Stabilization time (min)	min	60	60	60	60	
LNE						
Ambient temperature (goniophotometer)	°C	25.6	24.7	24.9	25.1	0.7
Ambient temperature (sphere system)	°C	24	26.2	24.3	26.2	0.7
Supply voltage measured (V)	V	12.01	220.06	220.06	219.98	0.10%
Stabilization time (min)	min	90	90	90	90	

Due to the uncertainty of the ambient temperature measurement (0.7°C for both labs), the tolerance requirement of 25.0 ± 1.2°C in CIE S 025 (acceptance interval is 0.5°C, equating to 0.7°C less than the tolerance interval) was not met in some cases. Thus, all measurement results of current, active power, total luminous flux, luminous efficacy, partial flux, and centre beam intensity were corrected to 25°C using the sensitivity coefficients in Table 5-1 so that the temperature requirements in CIE S 025 were met in all cases. No corrections were made for colour quantities, as the changes were practically negligible in all cases. No corrections were made for deviations of the supply voltage, as it always met the tolerance requirement of CIE S 025.

6.2 Reproducibility of artefacts

KILT measured each artefact set twice, before and after shipment and measurement by LNE. The differences in these two measurements (After – Before) are shown in Table 6-3. The artefacts reproduced reasonably well, but in some cases differences were considerable.

Table 6-3. (Relative) Difference between Before and After measurements at KILT; (After – Before)/Before (%) or (After – Before)

Quantity	ART-1		ART-2		ART-3		ART-4	
	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2
RMS current (DC current for Art-1)	-0.4%	-0.6%	0.0%	0.0%	0.1%	1.2%	0.2%	-0.4%
Active power (DC power for Art-1)	-0.5%	-0.7%	0.0%	0.1%	0.0%	-0.1%	0.3%	-0.8%
Power factor			0.001	0.001	-0.002	-0.013	0.000	-0.004
Total luminous flux	0.5%	1.2%	0.6%	-1.4%	0.2%	0.9%	1.7%	0.1%
Luminous efficacy	1.1%	1.9%	0.6%	-1.5%	0.2%	0.9%	1.3%	0.9%
Chromaticity u'	0.0001	0.0001	-0.0002	0.0008	0.0000	-0.0002	0.0001	0.0000
Chromaticity v'	-0.0002	0.0000	0.0000	0.0012	0.0001	0.0003	-0.0001	0.0001
Correlated colour temperature (K)	-2	-1	8	-94	-1	0	2	-4
Colour Rendering Index (CRI) R_a	-0.1	0.0	-0.1	-0.6	-0.2	-0.3	-0.1	-0.2
Gonio quantities								
Partial luminous flux cone angle 15°	-2.5%	0.4%						
Street light partial flux								
Forward light							2.6%	1.0%
Back light							-1.5%	-3.2%
Up-light (lm)							0.4	0.0
Centre beam intensity	-1.7%	-1.3%						
Beam Angle (°)	0.1	0.2						
Angular spatial colour uniformity	0.0003	-0.0003			0.0002	0.0001		

These artefact drift factors are considered in the uncertainty budget for the Assigned Value.

Each difference Δ_{stab} (relative or absolute differences) in this table is converted to a standard uncertainty u_{stab}, assuming that the drifts are rectangular distributions:

$$u_{stab} = \frac{\Delta_{stab}}{2\sqrt{3}} \qquad (1)$$

This is an uncertainty component related to artefact stability during the comparison, and it is used in the calculation of weighted mean for KILT and LNE results (see Section 6.5).

6.3 Nucleus Lab Measurement Results

The differences in the measurement between KILT and LNE for the two artefact sets, Set #1 and Set #2, are presented in Table 6-4. These are the averages of two measurements in each case and the averages of Before and After for KILT measurements.

Table 6-4. Differences between KILT and LNE results; (KILT – LNE)/LNE (%) or (KILT – LNE)

Quantity	ART-1		ART-2		ART-3		ART-4	
	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2
RMS current (DC current for Art-1)	-1.9%	-2.4%	0.1%	0.0%	-0.6%	-1.8%	0.3%	0.2%
Active power (DC power for Art-1)	-1.7%	-2.2%	0.1%	0.1%	0.9%	1.2%	0.3%	0.1%
Power factor			0.000	0.000	0.011	0.025	-0.001	-0.001
Total luminous flux	-1.3%	-0.7%	-2.4%	-2.6%	-0.7%	-1.0%	-0.6%	-0.7%
Luminous efficacy	0.5%	1.5%	-2.5%	-2.6%	-1.3%	-1.9%	-0.9%	-0.8%
Chromaticity u' - spatially averaged	-0.0003	-0.0002	-0.0001	0.0000	-0.0005	-0.0005	0.0006	0.0005
Chromaticity v' - spatially averaged	-0.0002	-0.0002	-0.0011	-0.0007	0.0003	0.0004	-0.0025	-0.0025
CCT (K) - spatially averaged	6	5	48	29	15	10	34	41
CRI Ra - spatially averaged	0.1	0.2	0.4	0.4	-0.2	-0.2	0.4	0.4
Goniophotometric quantities								
Partial luminous flux cone angle 15°	-5.0%	-5.1%						
Street light partial flux								
Forward light (%)							-2.3%	-2.3%
Back light (%)							1.3%	1.0%
Up-light (lm)							0.1	0.1
Centre beam intensity	-4.3%	-3.7%						
Beam Angle (°)	0.2	-0.2						
Angular spatial colour uniformity	0.0001	-0.0004			-0.0006	-0.0005		

The same calculation programmes for partial flux, beam angle, center beam intensity, and colour quantities developed by NIST are used by both labs in this comparison, so that there would be no issues related to differences in the calculation algorithms. The differences in partial luminous flux, appearing fairly large, are systematic, and may be related to angle accuracy of the goniophotometers because the partial flux of such a narrow beam lamp is very sensitive to even a very small angle error of the goniophotometer. Center beam intensity is also sensitive to alignment of the lamp.

6.4 Uncertainties of Measurements by KILT and LNE

The uncertainties (expanded uncertainty, *k*=2) of measurements by KILT and LNE are presented in Table 6-5 and Table 6-6.

Table 6-5. Uncertainties of Measurements by KILT (expanded uncertainty, *k*=2)

No.	Quantity	unit	ART-1	ART-2	ART-3	ART-4
Operating conditions						
	Ambient temperature	°C	0.7	0.7	0.7	0.7
	Supply voltage	%	0.13	0.22	0.22	0.22
General quantities						
1	RMS current (DC current for ART-1)	%	1.0	1.0	1.0	1.0
2	Active power	%	1.0	1.3	2.5	1.1
3	Power factor	1	-	0.01	0.01	0.01
4	Total luminous flux	%	2.0	1.5	1.5	1.5
5	Luminous efficacy	%	2.2	2.0	2.9	1.9
6	Chromaticity coordinate *u*'	1	0.0008	0.0008	0.0008	0.0012
	Chromaticity coordinate *v*'	1	0.0012	0.0012	0.0012	0.0016
7	Correlated colour temperature (K)	K	20	60	35	45
8	Colour Rendering Index (CRI) R_a	1	0.4	0.4	0.4	0.4
Goniophotometer quantities						
9	Luminous intensity distribution (cd) at [illegible]= 0	%	3.0	3.0	3.0	3.0
10	Partial luminous flux (15° cone angle)	%	4.0			
11	Street light partial flux					
	Street-side downward flux	%				3.0
	House-side downward flux	%				3.0
	Upward flux	lm				2.0
12	Centre beam intensity	%	3			
13	Beam angle	°	0.3			
14	Angular spatial colour uniformity Δ*u*'*v*'	1	0.0006		0.0007	

Table 6-6. Uncertainties of Measurements by LNE (expanded uncertainty, k=2)

No.	Quantity	unit	ART-1	ART-2	ART-3	ART-4
Operating conditions						
	Ambient temperature	°C	0.7	0.7	0.7	0.7
	Supply voltage	%	0.04	0.09	0.18	0.05
General quantities						
1	RMS current (DC current for ART-1)	%	1.00	1.00	1.00	1.00
2	Active power	%	0.70	0.50	0.69	0.51
3	Power factor	1	-	0.01	0.01	0.01
4	Total luminous flux	%	1.7	1.3	1.3	1.3
5	Luminous efficacy	%	1.8	1.4	1.5	1.4
6	Chromaticity coordinate *u*'	1	0.0007	0.0007	0.0007	0.0010
	Chromaticity coordinate *v*'	1	0.0010	0.0010	0.0010	0.0015
7	Correlated colour temperature (K)	K	15	45	25	35
8	Colour Rendering Index (CRI) R_a	1	0.3	0.3	0.3	0.3
Goniophotometer quantities						
9	Luminous intensity distribution (cd) at □□□□0	%	2.5	2.5	2.5	2.5
10	Partial luminous flux (15° cone angle)	%	3			
11	Street light partial flux					
	Street-side downward flux	%				1.8
	House-side downward flux	%				1.8
	Upward flux	lm				1.0
12	Centre beam intensity	%	2.5			
13	Beam angle	°	0.15			
14	Angular spatial colour uniformity Δ*u'v'*	1	0.0005		0.0005	

6.5 Calculation of Weighted Mean for KILT and LNE results

Each uncertainty value in Table 6-5 (KILT) and Table 6-6 (LNE) was converted to standard uncertainty, denoted u_1, u_2, respectively, and these were combined with the artefact stability uncertainty u_{stab} from Table 6-3 and eq. (1), for each artefact set, by

$$u_{1,s} = \sqrt{u_1^2 + u_{\mathrm{stab}}^2} \text{ and } u_{2,s} = \sqrt{u_2^2 + u_{\mathrm{stab}}^2} \tag{2}$$

Weighted means of the results of KILT (x_1) and LNE (x_2) for each artefact, each set and for each quantity were calculated based on the combined uncertainties above, $u_{1,s}$ and $u_{2,s}$ applying the equation published in the IC 2017 Technical Protocol:

$$\bar{x} = x_1 \cdot w_1 + x_2 \cdot w_2$$
$$\text{where } w_1 = \left[u_{1,s}^{-2} / \left(u_{1,s}^{-2} + u_{2,s}^{-2} \right) \right] \text{ and } w_2 = \left[u_{2,s}^{-2} / \left(u_{1,s}^{-2} + u_{2,s}^{-2} \right) \right] \tag{3}$$

With this formula, if the artefact change was large in Table 6-3, that artefact set data was given less weight in the weighted mean. The weighting factors w_1 and w_2 are shown in Table 6-7 and Table 6-8.

Table 6-7. Weighting Factors Used for KILT (w_1) and LNE (w_2) to Calculate Weighted Mean of Set 1

No.	Quantity	KILT				LNE			
		ART-1	ART-2	ART-3	ART-4	ART-1	ART-2	ART-3	ART-4
General Quantities									
1	RMS current (DC current for ART-1)	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
2	Active power	0.347	0.135	0.071	0.182	0.653	0.865	0.929	0.818
3	Power factor		0.500	0.500	0.500		0.500	0.500	0.500
4	Total luminous flux	0.422	0.433	0.430	0.453	0.578	0.567	0.570	0.547
5	Luminous efficacy	0.411	0.341	0.206	0.381	0.589	0.659	0.794	0.619
6	Chromaticity coordinate *u*'	0.434	0.435	0.434	0.410	0.566	0.565	0.566	0.590
	Chromaticity coordinate *v*'	0.411	0.410	0.410	0.468	0.589	0.590	0.590	0.532
7	Correlated colour temperature (K)	0.361	0.361	0.338	0.377	0.639	0.639	0.662	0.623
8	Colour Rendering Index (CRI) R_a	0.364	0.362	0.370	0.366	0.636	0.638	0.630	0.634
Goniophotometer quantities									
9	Luminous intensity distribution (cd) at □□= 0								
10	Partial luminous flux, 15° cone angle	0.380				0.620			
11	Street light partial flux								
	Street-side downward flux				0.343				0.657
	House-side downward flux				0.408				0.592
	Upward flux				0.206				0.794
12	Centre beam intensity	0.420				0.580			
13	Beam angle	0.206				0.794			
14	Angular spatial colour uniformity $\Delta u'v'$	0.429		0.343		0.571		0.657	

Table 6-8. Weighting Factors Used for KILT (w_1) and LNE (w_2) to Calculate Weighted Mean of Set 2

No.	Quantity	KILT				LNE			
		ART-1	ART-2	ART-3	ART-4	ART-1	ART-2	ART-3	ART-4
General Quantities									
1	RMS current (DC current for ART-1)	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
2	Active power	0.359	0.135	0.071	0.235	0.641	0.865	0.929	0.765
3	Power factor		0.500	0.500	0.500		0.500	0.500	0.500
4	Total luminous flux	0.429	0.447	0.437	0.429	0.571	0.553	0.563	0.571
5	Luminous efficacy	0.425	0.367	0.220	0.368	0.575	0.633	0.780	0.632
6	Chromaticity coordinate *u*'	0.434	0.452	0.435	0.410	0.566	0.548	0.565	0.590
	Chromaticity coordinate *v*'	0.410	0.435	0.412	0.468	0.590	0.565	0.588	0.532
7	Correlated colour temperature (K)	0.360	0.432	0.338	0.377	0.640	0.568	0.662	0.623
8	Colour Rendering Index (CRI) R_a	0.360	0.429	0.387	0.373	0.640	0.571	0.613	0.627
Goniophotometer quantities									
9	Luminous intensity distribution (cd) at □□= 0								
10	Partial luminous flux, 15° cone angle	0.361				0.639			
11	Street light partial flux								
	Street-side downward flux				0.452				0.548
	House-side downward flux				0.473				0.527
	Upward flux				0.200				0.800
12	Centre beam intensity	0.416				0.584			
13	Beam angle	0.260				0.740			
14	Angular spatial colour uniformity $\Delta u'v'$	0.418		0.339		0.582		0.661	

After determining all the weighted mean values for each artefact, the differences of each result of KILT and LNE from the weighted mean values were calculated for all quantities. The results are shown in Figure 6-1 through Figure 6-16.

These data are used to adjust (correct) all measurements made by KILT and LNE in the IC 2017 nucleus laboratory measurement round to make sure their results agree in principle (see next section). In these results, the deviations can come from systematic errors as well as some random variation. If the shifts from the weighted mean for Set #1 and Set #2 (two points connected by a line in the following figures) are relatively close, the deviation is considered to be caused primarily by systematic errors. If the shifts from the weighted means for Set #1 and Set #2 are not close together, then the deviation includes significant random variations.

The error bars in the following figures are expanded uncertainties (k=2) of each Nucleus Laboratory measurement of each artefact, combined with the artefact stability component. The error bars should cross the 0 % line (relative weighted mean value) for the results to be consistent statistically. If the error bars do not cross 0%, the uncertainty may be underestimated or there may have been some unknown uncertainty components not considered.

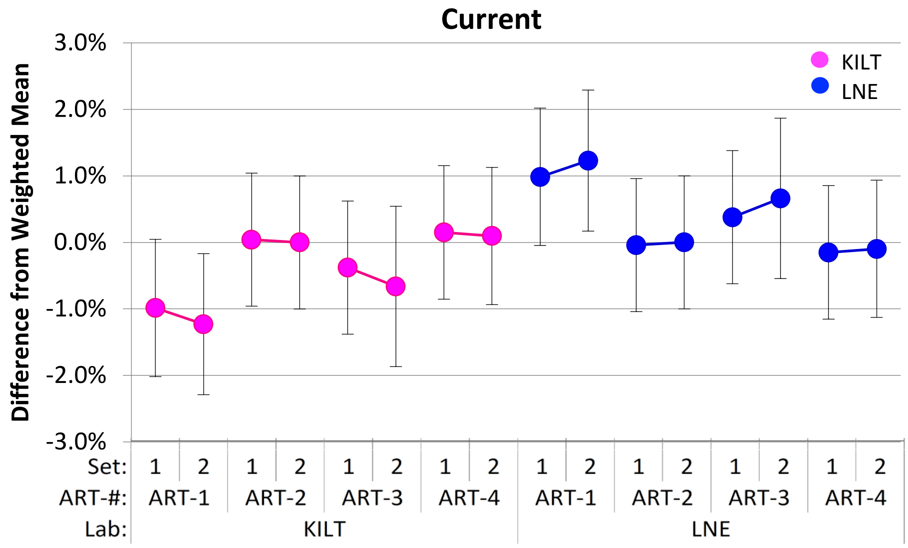


Figure 6-1. Deviation in DC current (ART-1) and RMS current (ART-2, ART-3, ART-4) from measured value to weighted mean for each artefact

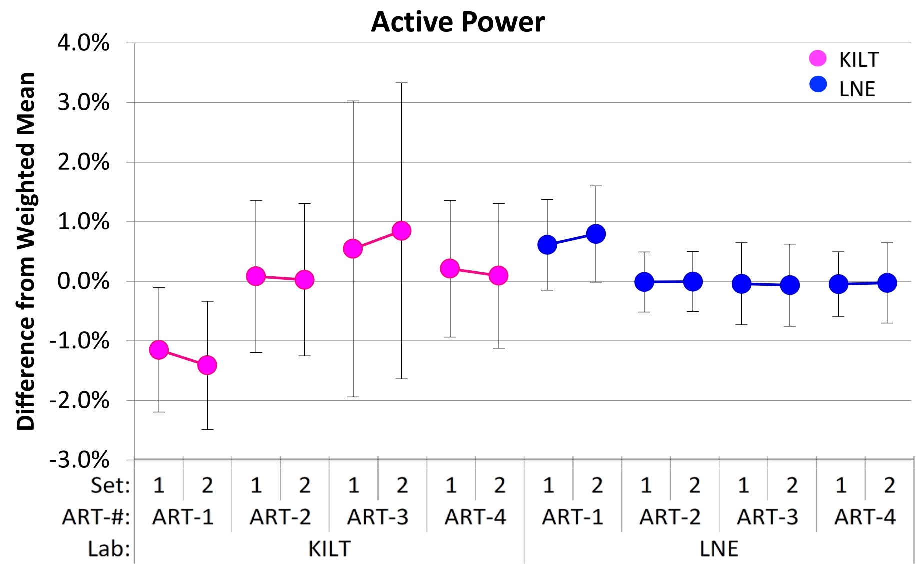


Figure 6-2. Deviation in active power from measured value to weighted mean for each artefact

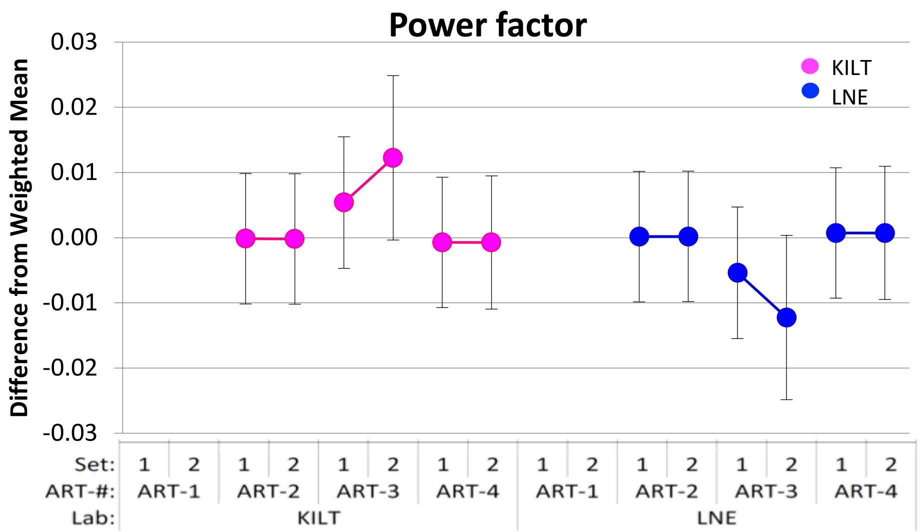


Figure 6-3. Deviation in power factor from measured value to weighted mean for each artefact

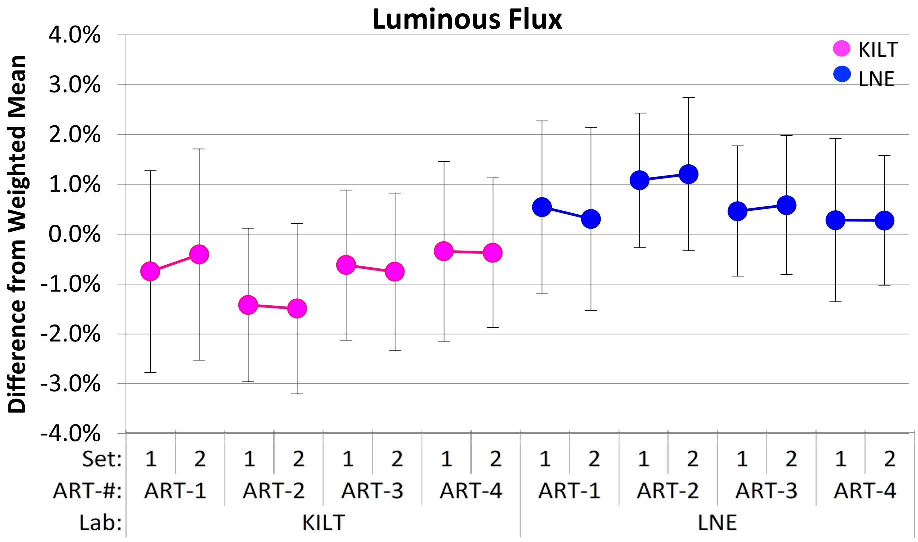


Figure 6-4. Deviation in total luminous flux from measured value to weighted mean for each artefact

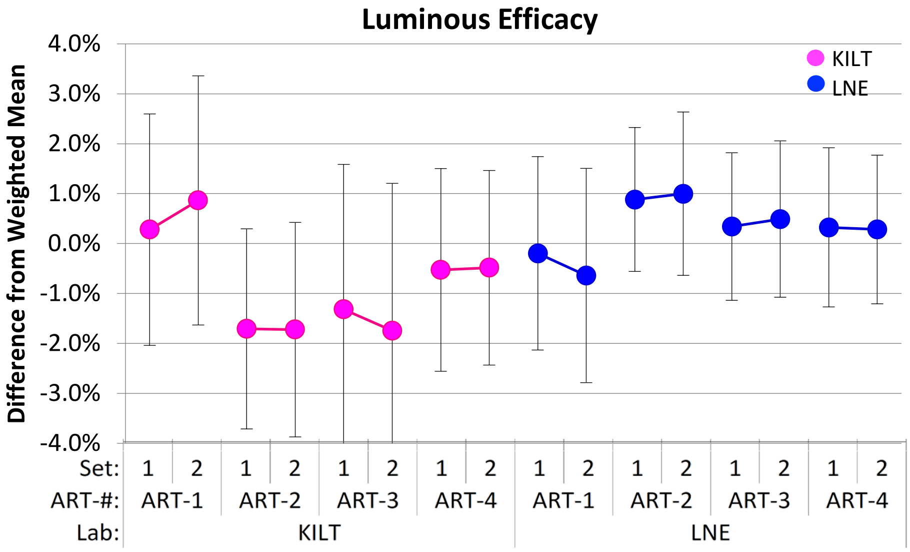


Figure 6-5. Deviation in luminous efficacy from measured value to weighted mean for each artefact

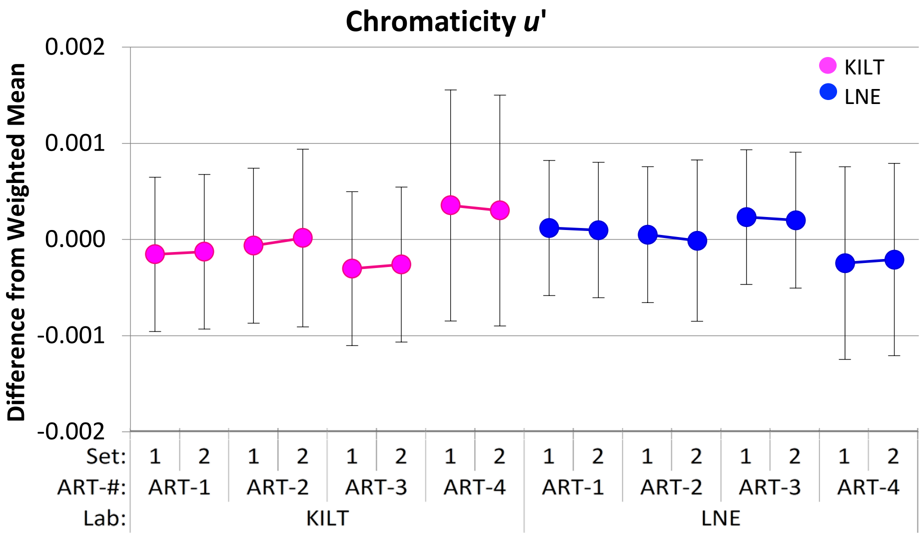


Figure 6-6. Deviation in chromaticity u' from measured value to weighted mean for each artefact

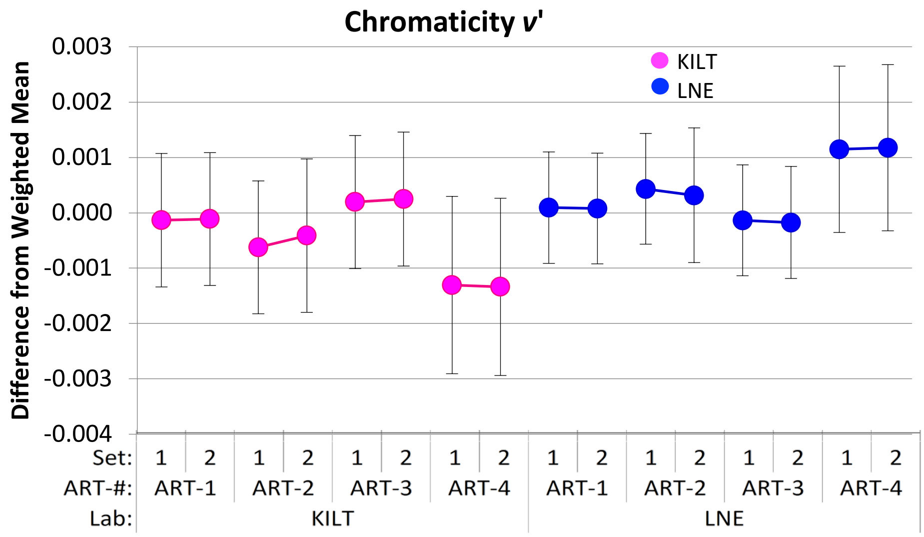


Figure 6-7. Deviation in chromaticity v' from measured value to weighted mean for each artefact

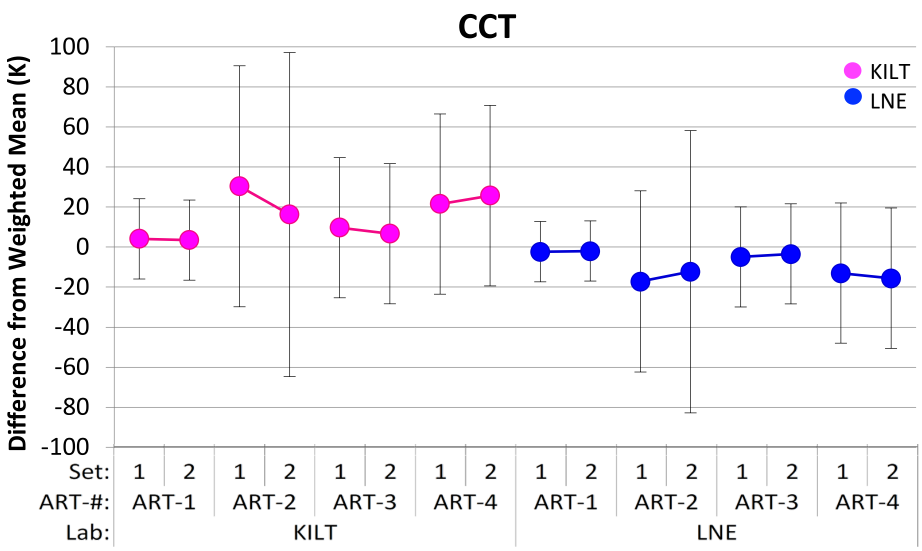


Figure 6-8. Deviation in CCT from measured value to weighted mean for each artefact

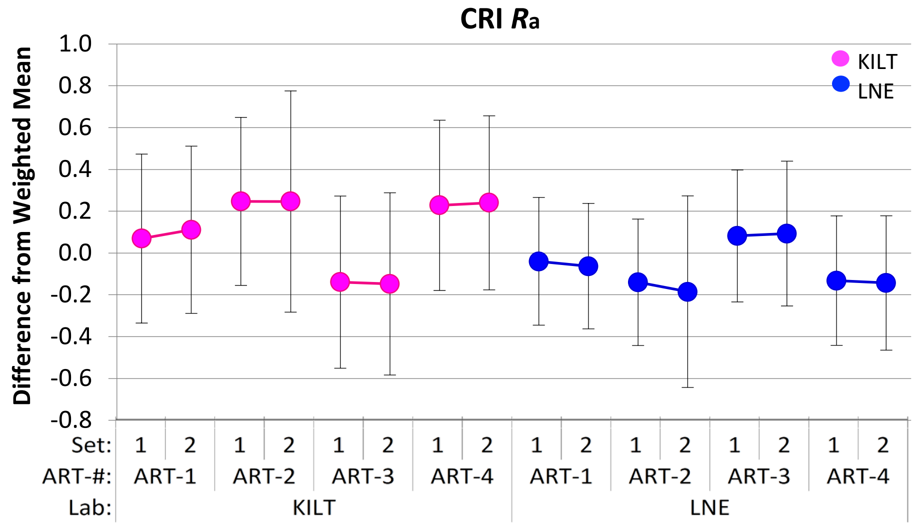


Figure 6-9. Deviation in CRI from measured value to weighted mean for each artefact

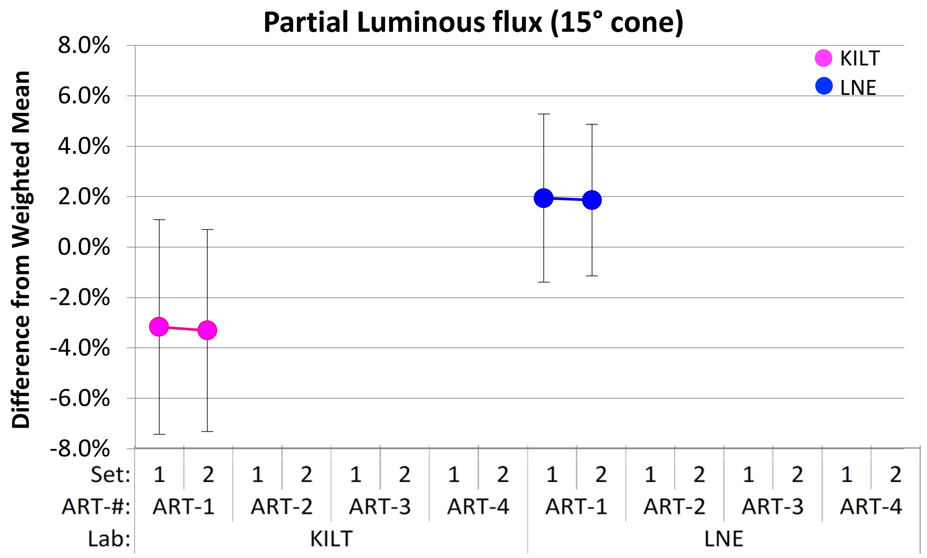


Figure 6-10. Deviation in partial luminous flux (15° cone) from measured value to weighted mean for ART-1

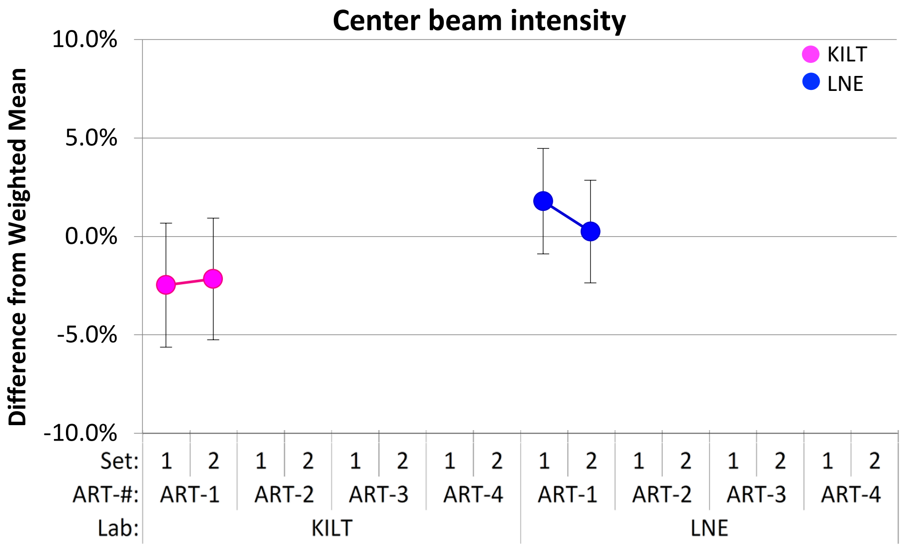


Figure 6-11. Deviation in centre beam intensity from measured value to weighted mean for ART-1

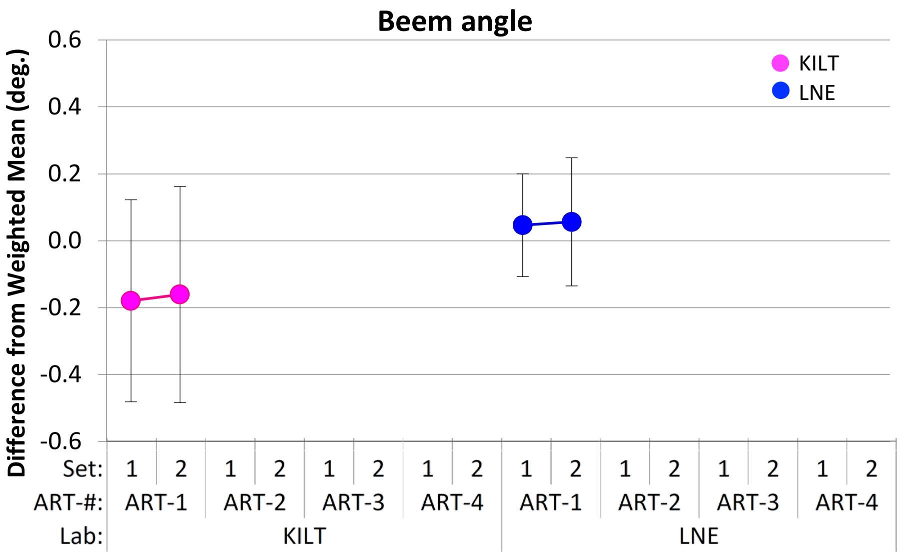


Figure 6-12. Deviation in beam angle from measured value to weighted mean for ART-1

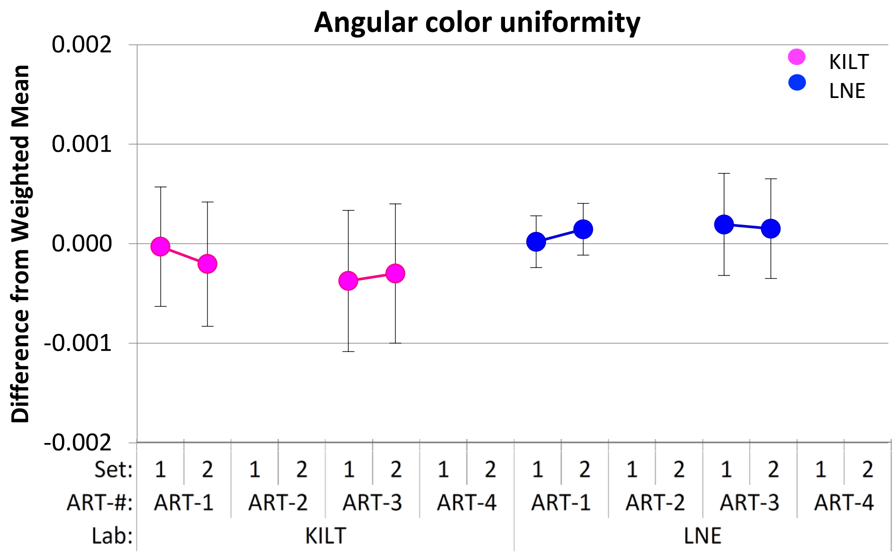


Figure 6-13. Deviation in colour uniformity from measured value to weighted mean for ART-1 and ART-3

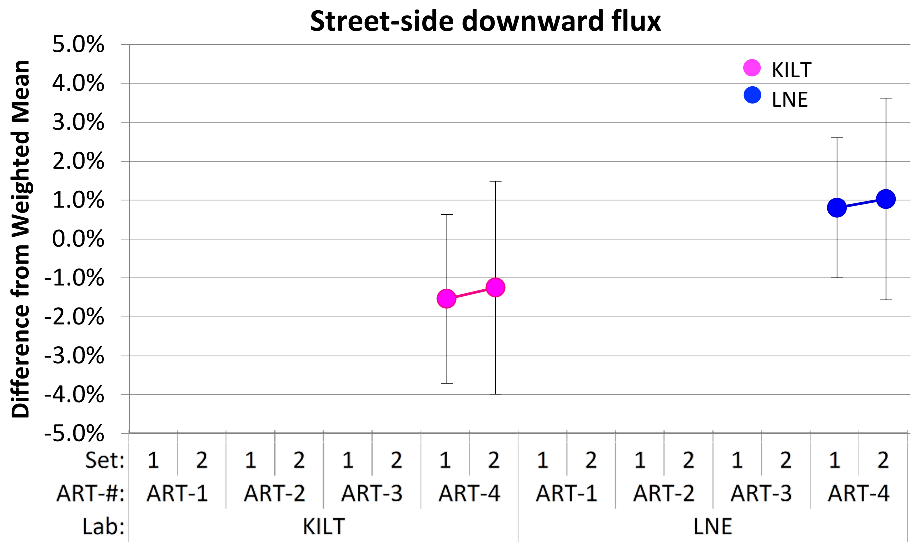


Figure 6-14. Deviation in street-side downward flux from measured value to weighted mean for ART-4

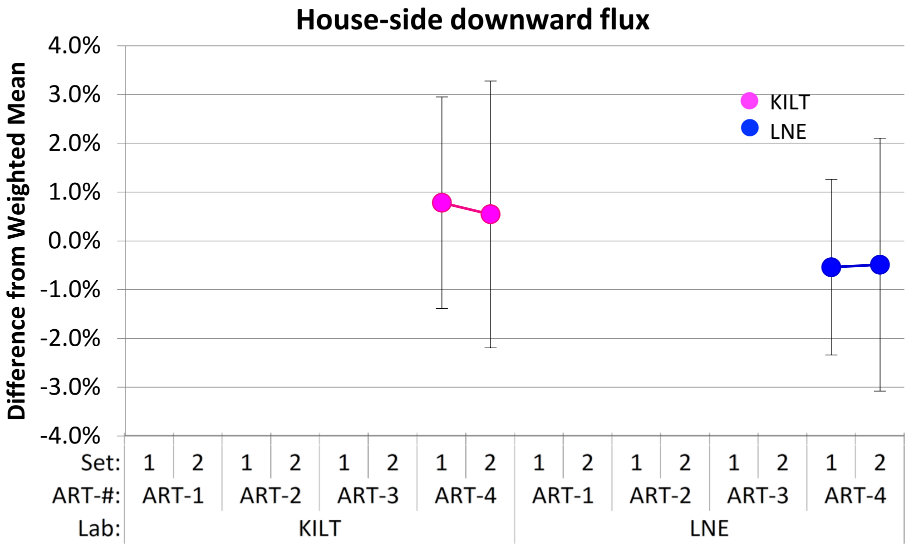


Figure 6-15. Deviation in house-side downward flux from measured value to weighted mean for ART-4

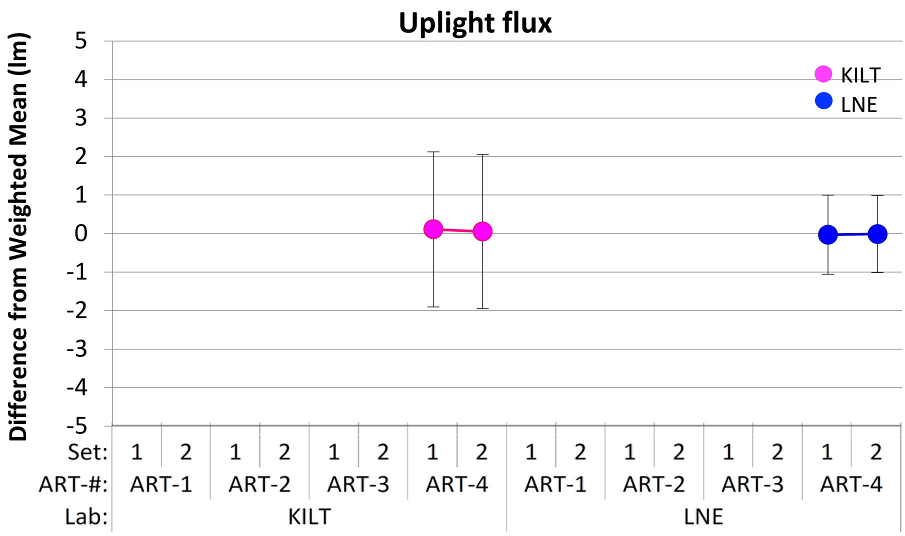


Figure 6-16. Deviation in uplight flux from measured value to weighted mean for ART-4

The uncertainties of the weighted mean values calculated by eq. (4) for each quantity x (to be used for Assigned Values) for each set were calculated using the following equation (also shown in IC 2017 Technical Protocol):

$$u(\bar{x}) = \left[1/\left(u_{1,s}^{-2} + u_{2,s}^{-2}\right)\right]^{1/2} \qquad (4)$$

The results of this calculation are shown in Table 6-9.

Table 6-9. Uncertainties of the weighted mean values (k=2)

Quantity	Set 1				Set 2			
	ART-1	ART-2	ART-3	ART-4	ART-1	ART-2	ART-3	ART-4
RMS current (DC current for Art-1)	0.73%	0.71%	0.71%	0.71%	0.75%	0.71%	0.85%	0.73%
Active power (DC power for Art-1)	0.62%	0.47%	0.66%	0.49%	0.65%	0.47%	0.66%	0.59%
Power factor		0.007	0.007	0.007		0.007	0.009	0.007
Total luminous flux	1.31%	1.01%	0.99%	1.21%	1.39%	1.14%	1.05%	0.98%
Luminous efficacy	1.49%	1.17%	1.32%	1.25%	1.63%	1.30%	1.38%	1.18%
Chromaticity u' - spatially averaged	0.0005	0.0005	0.0005	0.0008	0.0005	0.0006	0.0005	0.0008
Chromaticity v' - spatially averaged	0.0008	0.0008	0.0008	0.0011	0.0008	0.0009	0.0008	0.0011
CCT - spatially averaged	12	36	20	28	12	53	20	28
CRI Ra - spatially averaged	0.2	0.2	0.3	0.2	0.2	0.3	0.3	0.3
Goniophotometric quantities								
Partial luminous flux cone angle 15°	1.9%				1.9%			
Street light partial flux								
Forward light (%)				1.5%				1.4%
Back light (%)				1.4%				1.9%
Up-light (lm)				0.9				0.9
Centre beam intensity	2.0%				2.0%			
Beam Angle (°)	0.1				0.2			
Angular spatial colour uniformity	0.0004		0.0004		0.0004		0.0004	

6.6 Correction Factors for Assigned Values

Since the differences in results between KILT and LNE can be significant in some cases, it was decided to apply correction factors to force the two laboratories' results for each artefact to be equal (in principle) as described in IC 2017 Technical Protocol [1]. The correction factors were calculated from the weighted mean, as described below.

For quantities that use relative uncertainties (e.g., luminous flux), the correction factors c_1 for KILT, and c_2 for LNE, for each quantity *x* in each artefact set, are calculated using the following formulae:

$$c_1 = \frac{\bar{x}}{x_1},\ c_2 = \frac{\bar{x}}{x_2} \tag{5}$$

For quantities that use absolute uncertainties (e.g., chromaticity coordinates *u', v'*), the correction factors d_1 for KILT, and d_2 for LNE, for each quantity *x* in each artefact set, were calculated using the following formulae:

$$d_1 = \bar{x} - x_1,\ d_2 = \bar{x} - x_2 \tag{6}$$

The values of c_1, c_2, d_1, and d_2 for artefact sets #1 and #2 for each quantity were averaged.

The correction factors for each quantity and each artefact were calculated as the average of those for Set 1 and Set 2. The resulting correction factors are given in Table 6-10 and Table 6-11.

Table 6-10. Correction factors for KILT measurements to set Assigned Values

Quantity	factor	ART-1	ART-2	ART-3	ART-4
RMS current (DC for ART-1)	c_1	1.011	1.000	1.006	0.999
Active power	c_1	1.013	0.999	0.990	0.999
Power factor	d_1	0.000	0.000	-0.009	0.001
Total luminous flux	c_1	1.006	1.014	1.005	1.004
Luminous efficacy	c_1	0.994	1.017	1.013	1.005
Chromaticity coordinate u'	d_1	0.0001	0.0000	0.0003	-0.0003
Chromaticity coordinate v'	d_1	0.0001	0.0005	-0.0002	0.0013
Correlated colour temperature (K)	d_1	-4	-23	-8	-24
Colour Rendering Index (CRI) R_a	d_1	-0.1	-0.2	0.1	-0.2
Luminous intensity distributions					
Partial luminous flux (15° cone angle)	c_1	1.032			
Street light partial flux					
Street-side downward flux	c_1				1.014
House-side downward flux	c_1				0.993
Upward flux (lm)	d_1				*
Centre beam intensity	c_1	1.024			
Beam angle (°)	d_1	0.2			
Angular colour uniformity $\Delta u'v'$	d_1	0.0001		0.0003	

* No corrections are made for upward flux.

Table 6-11. Correction factors for LNE measurements to set Assigned Values

Quantity	factor	ART-1	ART-2	ART-3	ART-4
RMS current (DC for ART-1)	c_2	0.989	1.000	0.994	1.001
Active power	c_2	0.993	1.000	1.001	1.000
Power factor	d_2	0.000	0.000	0.009	-0.001
Total luminous flux	c_2	0.996	0.989	0.996	0.997
Luminous efficacy	c_2	1.004	0.991	0.997	0.997
Chromaticity coordinate u'	d_2	-0.0001	0.0000	-0.0002	0.0002
Chromaticity coordinate v'	d_2	-0.0001	-0.0004	0.0002	-0.0012
Correlated colour temperature (K)	d_2	2	15	4	14
Colour Rendering Index (CRI) R_a	d_2	0.05	0.16	-0.09	0.14
Goniophotometric quantities					
Partial luminous flux (15° cone angle)	c_2	0.981			
Street light partial flux					
Street-side downward flux	c_2				0.991
House-side downward flux	c_2				1.005
Upward flux (unit: lm)	d_2				*
Centre beam intensity	c_2	0.989			
Beam angle (unit: degree)	d_2	-0.05			
Angular colour uniformity $\Delta u'v'$	d_2	-0.0001		-0.0002	

* No corrections are made for upward flux.

The uncertainties of the resulting Assigned Values for each quantity, each artefact, were calculated by

$$u(X_{c1}) \approx \left[u^2(\bar{x}) + u_A^2(x_1) + u_A^2(X_1) \right]^{1/2} \tag{7}$$

where $u(\bar{x})$ is from eq. (4) or Table 6-9 (average of Set 1 and Set 2), $u_A(x_1)$ is a Type A component of the uncertainty in x_1 (Nucleus Lab comparison result), and $u_A(X_1)$ is a Type A component of the uncertainty in X_1 (IC 2017 measurement round result). The uncertainty of the Assigned Values from Nucleus Lab 2, $u(X_{C2})$, was calculated similarly.

Table 6-12 shows the reproducibility of measurements by KILT and LNE used as values for $u_A(x_1)$, evaluated from repeated measurements of each artefact.

Table 6-12. Reproducibility of measurements at Nucleus Lab during Nucleus Lab comparison (standard uncertainties). The values are in standard uncertainty.

Quantity	KILT				LNE			
	ART-1	ART-2	ART-3	ART-4	ART-1	ART-2	ART-3	ART-4
RMS current	0.17%	0.01%	0.04%	0.01%	0.00%	0.02%	0.10%	0.00%
Active power	0.14%	0.01%	0.04%	0.01%	0.00%	0.02%	0.79%	0.04%
Power factor	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Total luminous flux	0.14%	0.09%	0.21%	0.06%	0.10%	0.09%	0.10%	0.07%
Luminous efficacy	0.27%	0.09%	0.15%	0.03%	0.10%	0.11%	0.74%	0.03%
Chromaticity coordinate *u'*	0.0001	0.0004	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
Chromaticity coordinate *v'*	0.0001	0.0001	0.0001	0.0001	0.0001	0.0003	0.0001	0.0001
Correlated colour temperature (K)	1	29	5	3	1	17	4	3
Colour Rendering Index (CRI) R_a	0.06	0.06	0.06	0.05	0.12	0.05	0.05	0.05
Goniophotometric quantities								
Partial flux (15° cone angle)	0.45%				0.08%			
Street-side downward flux				0.06%				0.06%
House-side downward flux				0.04%				0.10%
Upward flux (unit: lm)				0.06				0.08
Centre beam intensity	0.05%				0.05%			
Beam Angle (Unit: deg.)	0.10				0.05			
Angular colour uniformity	0.0002		0.0002		0.0002		0.0002	

Table 6-13 shows the estimated reproducibility of measurements during the period of measurement rounds 1 through 3, used as values for $u_A(X_1)$, thus including the short term reproducibility shown in Table 6-12 plus estimated drifts of calibration of instruments during the measurement rounds. These values do not include reproducibility of artefacts due to transportation.

Table 6-13. Estimated Reproducibility of Measurements of Nucleus Laboratories over the course of Measurement Rounds. The values are in standard uncertainty.

Quantity	KILT				LNE			
	ART-1	ART-2	ART-3	ART-4	ART-1	ART-2	ART-3	ART-4
RMS current	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Active power	0.17%	0.13%	0.25%	0.11%	0.07%	0.06%	0.79%	0.07%
Power factor		0.001	0.001	0.001		0.001	0.001	0.001
Total luminous flux	0.2%	0.2%	0.3%	0.2%	0.2%	0.2%	0.2%	0.1%
Luminous efficacy	0.3%	0.2%	0.3%	0.2%	0.2%	0.2%	0.8%	0.1%
Chromaticity coordinate *u'*	0.0002	0.0004	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Chromaticity coordinate *v'*	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0002	0.0002
Correlated colour temperature (K)	2.1	30.5	6.7	6.8	2.0	18.9	5.4	5.8
Colour Rendering Index (CRI) R_a	0.10	0.10	0.10	0.10	0.13	0.10	0.10	0.10
Goniophotometric quantities								
Partial flux (15° cone angle)	2.00%				0.26%			
Street-side downward flux				0.50%				0.19%
House-side downward flux				0.50%				0.20%
Upward flux (unit: lm)				1.00				1.00
Centre beam intensity	0.3%				0.26%			
Beam Angle (unit: degree)	0.30				0.10			
Angular colour uniformity	0.0003		0.0003		0.0003		0.0003	

From the values in Table 6-9, Table 6-12 and Table 6-13, the expanded uncertainties (k=2) of the Assigned Values are shown in Table 6-14.

Table 6-14. Expanded uncertainties (k=2) of the Assigned Values

Quantity	KILT				LNE			
	ART-1	ART-2	ART-3	ART-4	ART-1	ART-2	ART-3	ART-4
RMS current	0.90%	0.74%	0.82%	0.75%	0.77%	0.74%	0.86%	0.75%
Active power	0.77%	0.54%	0.84%	0.59%	0.65%	0.48%	2.34%	0.56%
Power factor		0.007	0.008	0.007		0.007	0.009	0.007
Total luminous flux	1.5%	1.2%	1.2%	1.1%	1.4%	1.1%	1.1%	1.1%
Luminous efficacy	1.8%	1.3%	1.5%	1.3%	1.6%	1.3%	2.5%	1.3%
Chromaticity coordinate u'	0.0007	0.0014	0.0007	0.0009	0.0007	0.0008	0.0007	0.0009
Chromaticity coordinate v'	0.0009	0.0010	0.0009	0.0012	0.0009	0.0012	0.0009	0.0012
Correlated colour temperature (K)	13	95	26	31	13	68	25	31
Colour Rendering Index (CRI) R_a	0.33	0.37	0.35	0.34	0.43	0.37	0.34	0.34
Goniophotometric quantities								
Partial flux (15 ° cone angle)	4.5%				2.0%			
Street-side downward flux				1.7%				1.5%
House-side downward flux				1.9%				1.7%
Upward flux (unit: lm)				2.2				2.2
Centre beam intensity	2.1%				2.1%			
Beam Angle (unit: degree)	0.65				0.27			
Angular spatial colour uniformity	0.0008				0.0008			

7 SDPA values for calculation of z'

The *z'* score for the results of participants in the measurement rounds will be calculated by:

$$z' = \frac{x - X}{\sqrt{\hat{\sigma}^2 + u_X^2 + u_{\text{drift}}^2}} \quad (8)$$

where x is the participant's result and X is the Assigned Value. $\hat{\sigma}$ is the SDPA value (Standard Deviation for Proficiency Assessment) which in this IC test is considered to be the generic standard uncertainty of participants' measurements. The u_x is the standard uncertainty of the Assigned Value (1/2 of the values in Table 6-14), and u_{drift} was calculated, as prescribed in the IC 2017 Technical Protocol [1], by:

$$u_{\text{drift}} = \frac{0.8 \cdot \hat{\sigma}}{2\sqrt{3}}. \quad (9)$$

In IC 2017, z' scores (and E_n numbers) are reported only for the eight quantities compared in IC 2013. The SDPA values for these eight quantities are determined from the robust standard deviations (for all artefacts) of the goniophotometer participants' data in IC 2013 [2] as shown in Table 7-1. The robust standard deviation values of CCT are adjusted for the CCTs of each artefact in IC 2017.

Table 7-1. SDPA Values for IC 2017

Quantity	ART-1	ART-2	ART-3	ART-4
RMS current	1.8%	1.8%	1.8%	1.8%
Active power	0.93%	0.93%	0.93%	0.93%
Power factor	0.013	0.013	0.013	0.013
Total luminous flux	2.5%	2.5%	2.5%	2.5%
Luminous efficacy	2.7%	2.7%	2.7%	2.7%
Chromaticity coordinate *u'*	0.0016	0.0016	0.0016	0.0016
Chromaticity coordinate *v'*	0.0017	0.0017	0.0017	0.0017
Correlated colour temperature (K)	20	104	40	56
Colour Rendering Index (CRI) R_a	0.5	0.5	0.5	0.5

The results for goniophotometric quantities are considered for technical study purposes in this comparison, thus their z' scores will not be calculated.

8 Conclusions

The comparison of measurements of the IC 2017 artefacts by the two Nucleus Laboratories was conducted. The differences of results between KILT and LNE for all measurement quantities and for all artefacts were evaluated, together with their measurement uncertainties. The differences were found to be within the uncertainties of the comparison results (error bars cross the 0 % line) in most cases. There were a few cases in RMS current and active power, where the differences were slightly larger than the uncertainties. The differences found are considered largely to be caused by systematic uncertainties because the results for the two sets of artefacts are highly correlated in all cases. To bring equivalence between the two Nucleus Laboratories' measurements, correction factors (based on weighted means of the two laboratories results) for their measurements were determined for all quantities and all artefacts; and will be applied to all measurements in the comparison rounds of IC 2017. Finally, the SDPA values will be applied to the analyses of all participants results reported.

References

1. Solid State Lighting Annex: Interlaboratory Comparison 2017 (IC 2017), Technical Protocol version 1.0; Yoshi Ohno, Sangkyoo Jeon, Jimmy Dubard. Published: 30 June 2017. Link: https://ssl.iea-4e.org/files/otherfiles/0000/0117/IC_2017_Technical_Protocol_v.1.0_final.pdf

2. Solid State Lighting Annex: 2013 Interlaboratory Comparison, Final Report. Yoshi Ohno, Koichi Nara, Elena Revtova, Wei Zhang, Tatsuya Zama, Cameron Miller. Published: 10 September 2014. Link: http://ssl.iea-4e.org/files/otherfiles/0000/0067/IC2013_Final_Report_final_10.09.2014a.pdf

3. International Bureau of Weights and Measures (BIPM) Key Comparison Database, Appendix C Calibration and Measurement Capabilities, https://kcdb.bipm.fr (search Photometry and Radiometry, then France)