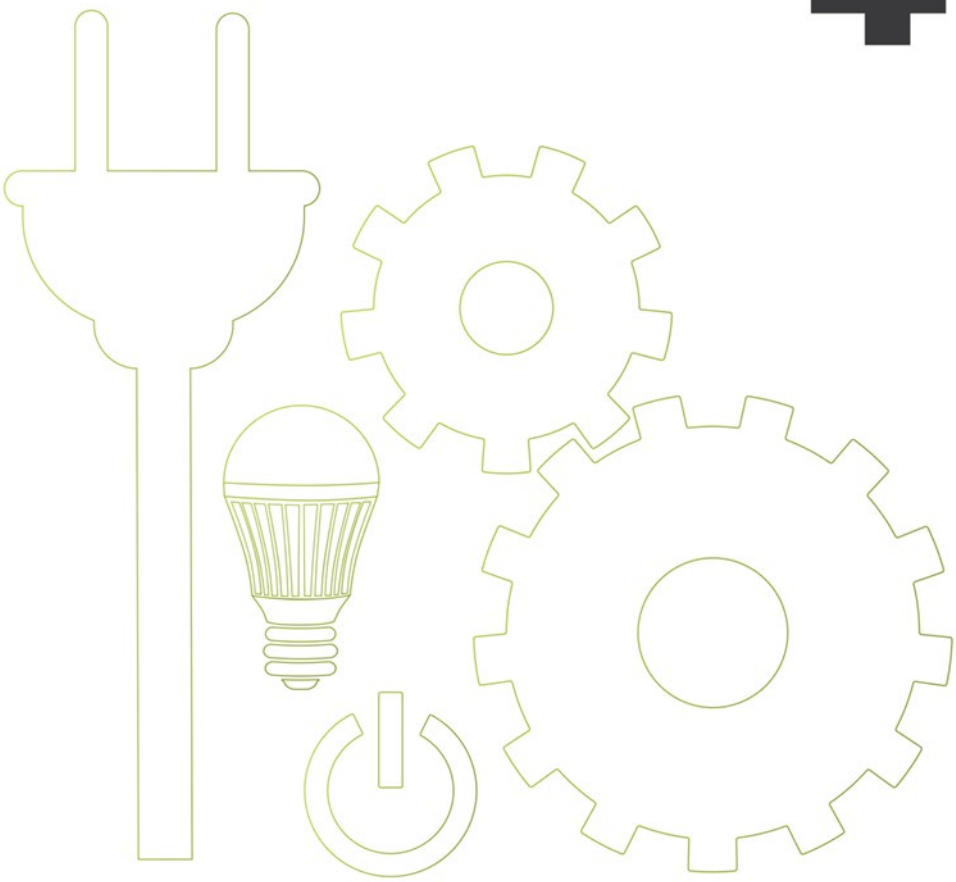
Energy Efficient End-use Equipment
International Energy Agency



Solid State Lighting Annex
IC 2023: Interlaboratory Comparison on Measurement of Temporal Light Modulation

Technical Protocol

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

iea Energy Technology Network

25 September 2023

IEA 4E Solid State Lighting Annex
IC 2023: Interlaboratory Comparison – Measurement of Temporal Light Modulation
Technical Protocol

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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 solid state lighting. This international collaboration was established by the governments of Australia, Denmark, France, Japan, The Netherlands, the Republic of Korea, Sweden, United Kingdom and the United States of America. Further information on the IEA 4E SSL Annex is available from: http://ssl.iea-4e.org/

About the IEA Implementing Agreement on Energy Efficient End-Use Equipment (4E) is an International Energy Agency (IEA) Implementing Agreement established in 2008 to support governments to formulate effective policies that increase production and trade in efficient electrical end-use equipment. Globally, electrical equipment is one of the largest and most rapidly expanding areas of energy consumption which poses considerable challenges in terms of economic development, environmental protection and energy security. As the international trade in appliances grows, many of the reputable multilateral organisations have highlighted the role of international cooperation and the exchange of information on energy efficiency as crucial in providing cost-effective solutions to climate change. Twelve countries have joined together to form 4E as a forum to cooperate on a mixture of technical and policy issues focused on increasing the efficiency of electrical equipment. But 4E is more than a forum for sharing information – it initiates projects designed to meet the policy needs of participants. Participants find that pooling of resources is not only an efficient use of available funds, but results in outcomes which are far more comprehensive and authoritative. The main collaborative research and development activities under 4E include:

- The Electric Motor Systems Annex (EMSA)
- The Mapping and Benchmarking Annex
- The Solid State Lighting Annex (SSL)
- The Electronic Devices and Networks Annex (EDNA)

Current members of 4E are: Australia, Austria, Canada, China, Denmark, the European Commission, France, Japan, Korea, The Netherlands, New Zealand, Sweden, Switzerland, 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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Acronyms and Abbreviations

4E	Energy Efficient End-use Equipment
AC	Alternating Current
ART	Artefact
CCT	Correlated Colour Temperature
cd	candela
CIE	Commission Internationale de l'Éclairage (International Commission on Illumination)
CIPM	International Committee for Weights and Measures
CMA	China Inspection Body and Laboratory Mandatory Approval
CNAS	China National Accreditation Service
CRI	Colour Rendering Index
DC	Direct Current
DUT	Device Under Test
EN	European Norm
Hz	hertz
IC	Interlaboratory Comparison
ID	Identification
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ISO	International Standardisation Organisation
ITR	Individual Test Report
KS	Korean Industrial Standards
LED	Light Emitting Diode
LCS	Luminaire Classification System
lm	lumen
MRA	Mutual Recognition Arrangement
NLC	Nucleus Lab Comparison
P_{st}^{LM}	Short-term Flicker Indicator
PT	Proficiency Test
PWM	Pulse Width Modulation
RMS	Root Mean Square
SDPA	Standard Deviation for Proficiency Assessment
SSL	Solid State Lighting
SVM	Stroboscopic Effect Visibility Measure
THD	Total Harmonic Distortion
TLM	Temporal Light Modulation
UK	United Kingdom
USA	United States of America
VAC	Voltage, Alternating Current
W	watt

1 Introduction

The International Energy Agency (IEA) 4E Solid State Lighting Annex is conducting an international Interlaboratory Comparison (IC 2023) on the measurement of Temporal Light Modulation (TLM) of solid state lighting (SSL) products. This work builds on the SSL Annex's experience from the previous two interlaboratory comparisons on measurement of SSL products: IC 2013 (IEA 4E SSL Annex, 2014) and IC 2017 (IEA 4E SSL Annex, 2021). IC 2023 is organised to compare the measurements of the comparison artefacts *for short-term flicker indicator* (P_{st}^{LM}) defined in IEC TR 61547-1 (IEC, 2020) and *stroboscopic effect visibility measure* (SVM, M_{VS}) defined in IEC TR 63158 (IEC, 2018).

Four LED lamps with different TLM characteristics and a TLM generator for a technical study are used as the comparison artefacts. The comparison will investigate the degree of agreement in the measurements of these TLM quantities among the participants and analyse problems in participants' measurements results as well as possible general problems in the test methods. This Interlaboratory Comparison (IC) is not only a technical study, it is designed in compliance with ISO/IEC 17043 (ISO/IEC, 2023) to serve as a proficiency test for SSL testing accreditation programmes that recognise this comparison, as was done in IC 2013 and IC 2017.

This international IC will also be linked to two regional interlaboratory comparisons that will be conducted about the same time and include the same types of comparison artefacts; they are European Metrology Programme for Innovation and Research (EMPIR) Metrology for Temporal Light Modulation (MetTLM) project and the China National Standard Verification Programme: Laboratory Comparison on Temporal Lighting Modulation (China GBV-LC TLM).

2 Nucleus Laboratories and Link Laboratories

2.1 Comparison Scheme

There are two types of Nucleus Laboratories in this IC, one is the *Operational Nucleus Laboratory* that will perform measurement rounds with the participants, and the other is *Supporting Nucleus Laboratory* that participated in the comparisons among all Nucleus Laboratories. The Nucleus Laboratories were chosen among the laboratories that have recognition for optical radiation measurements and have suitable facilities and experiences in TLM measurements and have resources to serve this IC. This document describes the technical protocol used by the participating laboratories as well as by Nucleus Laboratories. There are two Operational Nucleus Laboratories and three Supporting Nucleus Laboratories as described in the following subsections.

To make IC 2023 widely useful, this IC will be linked with EMPIR MetTLM project, which will conduct an interlaboratory comparison of measurement of TLM which, among their artefacts, will includes the same artefacts as IC 2023 and using nearly the same Technical Protocol. In addition, this IC will also be linked to China GBV-LC TLM, which is organised by National Lighting Test Centre (Beijing, China) for participants within China for measurement of TLM. Both of these regional ICs have appointed *Link Laboratories* that will participate in the IC 2023 Nucleus Laboratory Comparison to establish links to the reference values in IC 2023.

Prior to IC 2023 measurement rounds, a Nucleus Laboratory Comparison (NLC) was conducted to verify agreements of measurements among all Nucleus Laboratories to establish reference values for artefacts as well as linking scales for the Link Laboratories. The NLC used an earlier draft version of the IC 2023 Technical Protocol (this document). The IC 2023 Technical Protocol was finalised now that the NLC has been completed.

Figure 1 illustrates the structure of IC 2023. The NLC (red circle) was conducted first to compare measurements by the two Operational Nucleus Laboratories, the three Supporting Nucleus Laboratories and the three Link Laboratories (two of which are also serving as Supporting Nucleus Laboratories). The NLC established the reference values for IC 2023 main round (black circle) and the linking data for the two regional comparisons (blue and purple circles).

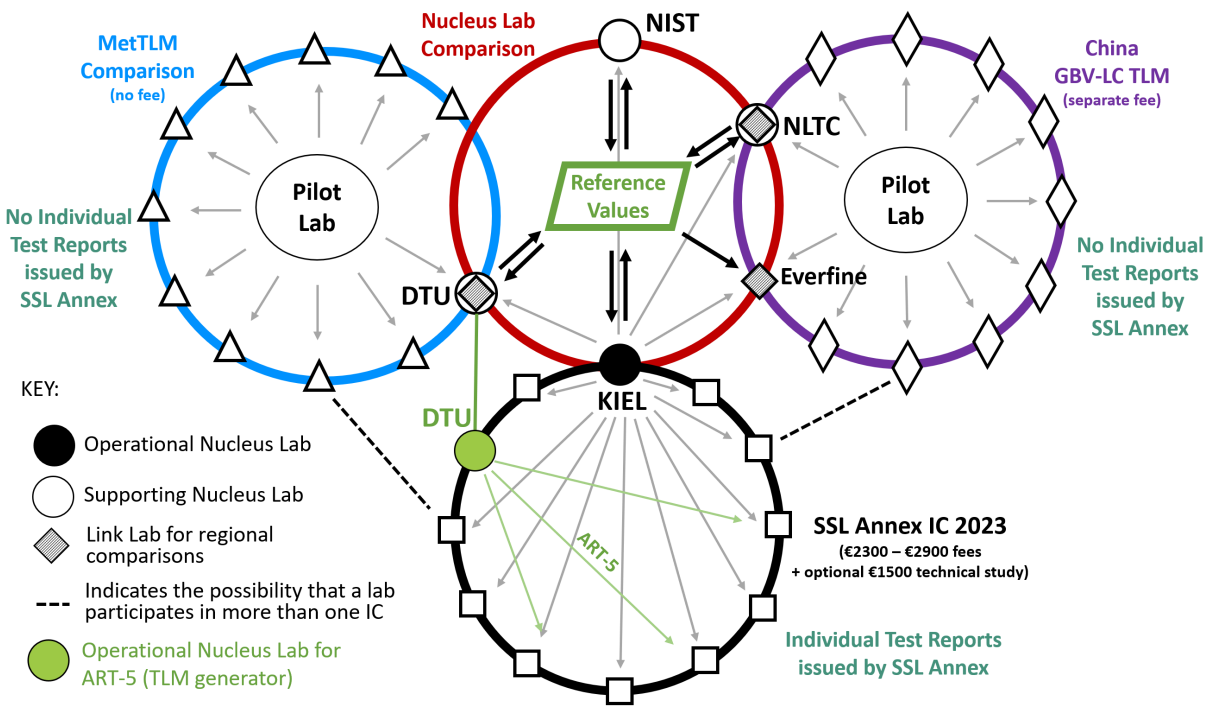

Figure 1. IC 2023 structure, with Nucleus Lab Comparison (red circle), measurement round (black circle) and two linked regional comparisons (blue and purple circles)

IC 2023 lamp artefact (ART-1 to 4) measurement rounds will be conducted as bilateral comparisons (a star-type comparison) between each participating laboratory and the Operational Nucleus Laboratory. The optional IC 2023 technical study using a wave-form generator (ART-5) will be conducted as a modified star-type comparison, where one generator is shared with two participants between each Operational Nucleus Lab measurement. The details of the IC 2023 measurement rounds will be finalised after participant registration is complete and the final number of participants is known.

2.2 Operational Nucleus Laboratories

KIEL Institute
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KIEL Institute is the Korean Industrial Standards (KS) certification body and has been accredited for ISO/IEC 17025 by Korea Laboratory Accreditation Scheme for optical radiation measurements. KIEL has been also accredited as the KS testing laboratory from Korean Agency for Technology and Standards and high efficiency certification programme testing lab from Korea Energy Agency for photometry, and has developed the safety and photometric performance requirement for KS as a Cooperation Organisation for Standards Development. KIEL also provides testing services for the Design Lights Consortium and ENERGY STAR programme as an United States Environmental Protection Agency recognised laboratory, and designated as Certification Body Testing Laboratory of IEC System for Conformity Assessment Schemes for Electrotechnical Equipment and Components.

KIEL Institute will be the Operational Nucleus Laboratory for the lamp artefacts, ART-1, ART-2, ART-3 and ART-4.

Technical University of Denmark (DTU)
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E-mail address: cadh@dtu.dk
Phone number: +45 46 77 45 13

DTU is the Technical University of Denmark, which in the Department of Electrical and Photonics Engineering has a research, education and testing laboratory for optical radiation, in photometry and spectroradiometry. DTU runs research and development projects on lighting metrology, LED technology, SSL and laser lighting and participates in EURAMET projects functioning as an independent university testing laboratory.

DTU will be the Operational Nucleus Laboratory for the optional technical study using a wave form generator, ART-5.

2.3 Supporting Nucleus Laboratories

National Institute of Standards and Technology
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NIST is the national metrology institute for the United States, maintaining photometric and radiometric units (such as lumen, candela, watt) and disseminates standards for luminous flux, luminous intensity, spectral irradiance, etc. NIST's calibration and measurement capabilities for many photometric and radiometric quantities are certified and published by International Committee for Weights and Measures (CIPM) under the framework of CIPM Mutual Recognition Arrangement (MRA) (BIPM, 2023). NIST is self-accredited for ISO/IEC 17025. NIST provides a wide variety of calibration services in photometry and radiometry. NIST led the previous two SSL Annex interlaboratory comparisons, IC 2013 and IC 2017. NIST also led development of CIE S 025.

National Lighting Test Centre (NLTC)
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NLTC (National Lighting Test Centre) is an independent third-party technical service agency which conducts testing, researching, standardisation, training, and more. NLTC's capability for testing lighting and related products has been accredited by China National Accreditation Service (CNAS) and China Inspection Body and Laboratory Mandatory Approval (CMA). NLTC

has led or participated in the development of many international and national (China) standards on lighting. NLTC contributed to the previous SSL Annex interlaboratory comparison, IC 2013, as a nucleus laboratory.

Technical University of Denmark (DTU)
The Technical University of Denmark (DTU) listed in Section 2.2 above also serves as a supporting nucleus laboratory to IC 2023.

2.4 Link Laboratories

Technical University of Denmark (DTU)
For MetTLM comparison, Technical University of Denmark (DTU) listed in Section 2.2 above serves as the link laboratory to IC 2023.

National Lighting Test Centre (NLTC)
For the China GBV-LC TLM comparison, there are two link laboratories to IC 2023. National Lighting Test Centre (NLTC) listed in Section 2.3 above is one of them.

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EVERFINE Test (EVERFINE Test and Calibration Technology Co., Ltd) is an independent third-party laboratory that provides services of testing, calibration, accreditation consulting, product certification and more. It has established facilities and capabilities of photometric and electrical calibration, lighting tests, medical equipment tests, fire protection tests, automotive parts tests, and more. The laboratories of EVERFINE Test have been accredited by CNAS, CMA and the National Voluntary Laboratory Accreditation Program (USA).

EVERFINE Test and Calibration Technology Company, Limited (EVERFINE) is the second link laboratory for China GBV-LC TLM comparison.

3 Comparison Artefacts

The artefacts were selected from the current market of LED lamp products. The selected four LED lamp models (ART-1 to ART-4) are listed in Table 1. The original plan was to cover large ranges of P_{st}^{LM} and SVM values, however, the range of P_{st}^{LM} values among the lamps on

the market were limited. All the artefact LED lamps were seasoned for 24 hours and tested for stability and reproducibility by the Operational Nucleus laboratory as described in Annex 1 of this document.

ART-5 (TLM waveform generator) is intended to cover some ranges of P_{st}^{LM} and SVM values that are not available in the selected lamps, and for special conditions for technical study purposes. These measurements were evaluated in the NLC, and it was decided to offer ART-5 to IC 2023 participants as an optional additional technical study in the measurement rounds.

Multiple lamps for each artefact have been prepared for use in IC 2023 measurement rounds. Each lamp has been given an ID number (e.g., 1-01, 1-02, ...). Several sets of artefacts will be used in a measurement round with different participants, and it may be required to have two or three measurement rounds to complete IC 2023. It is expected that some of the artefact sets will be re-used in a subsequent measurement round, in which case the lamps will be re-numbered.

Table 1. Artefact Set for IC 2023

	Artefact	Photo	Electrical Rating	Feature	ID# for NLC
ART-1	LED lamp		230 VAC, 50Hz, 3.8 W	low SVM (<0.5) P_{st}^{LM} (<0.5)	1-01 to 1-08
ART-2	LED lamp		230 VAC, 50Hz, 3.5 W	Higher SVM (0.5 – 1.0) P_{st}^{LM} (<0.5)	2-01 to 2-08
ART-3	LED lamp		230 VAC, 50Hz, 5 W	High SVM (>2.0) P_{st}^{LM} (<0.5)	3-01 to 3-08
ART-4	LED lamp (complex waveform)		230 VAC, 50Hz, ~2.5 W	High SVM (>1.0) P_{st}^{LM} (<0.5)	4-01 to 4-08
Artefact for Optional Technical Study					
ART-5	TLM waveform generator (VISO Systems Labarazzi)		100 VAC to 230 VAC	Five preset test profiles	**LAZ-1** (L1-01 to L1-05) **LAZ-2** (L2-01 to L2-05)

All LED lamps are omni-directional lamps with E27 screw base and are rated for 230 VAC, 50 Hz.

ART-5 is a programmable light source TLM waveform generator where the light is emitted from the back of the unit. This generator has been programmed with custom firmware to produce five preset waveforms to test the laboratory's TLM measurement capabilities. A general description of the five waveforms appears below:

1) Sine wave with moderate modulation depth at slightly different modulation frequency from 120Hz;
2) Pulse Width Modulation (PWM) wave with low modulation depth and mid-range duty cycle at slightly different frequency from 100 Hz;
3) High P_{st}^{LM} and low SVM (multiple low frequency components);

4) PWM wave at several times higher frequency than 100 Hz, high modulation depth and low duty cycle (multiple high frequency components); and
5) Sine wave mix of multiple frequencies with mid-range modulation depth.

4 Properties Measured for Comparison

Table 2 shows the main measurement quantities to be compared for all participants. The results of these quantities will be used for proficiency test purposes, and the uncertainties (95% confidence interval, or coverage factor k=2) of the reported values of both quantities are required. The absolute uncertainty (values in P_{st}^{LM} or SVM) shall be used. Do not use relative uncertainty (in %). In situations where participants report results without an uncertainty value, the E_n number will not be calculated, which may compromise a participant's ability to use the IC 2023 results for proficiency test purposes.

Table 2. Main quantities for comparison

	Measurement Quantity	Symbol
1	Short-term flicker indicator	P_{st}^{LM}
2	Stroboscopic effect visibility measure (SVM)	M_{VS}

Table 3 shows the quantities that are optional for the participants who are capable of measuring these metrics, for the purpose of technical study. The comparison will be only among the participants who reported these results and the Nucleus Laboratories that measured these quantities in Nucleus Laboratory Comparison.

Table 3. Optional quantities for comparison

	Metric	Symbol
3	Flicker Index (FI)[1)]	I_F
4	M_p[2)]	M_P
5	Percent flicker for combined frequencies ≤ 200 Hz [3)] (@100% light output)	

1) Flicker Index is defined in the reference (CIE, 2020)
2) M_p is defined in the reference (ASSIST, 2015)
3) California Energy Commission, JA8/JA10 (CEC, 2022)

Table 4 lists the measurement conditions and some other measurement results to be reported, and Table 5 shows laboratory information to be reported by all participants. The Results Report form is attached at the end of this protocol document.

Table 4. Measurement conditions and other results to be reported

	Other results reported
6	Supply voltage measured (and uncertainty)
7	RMS current of the lamp (and uncertainty)
8	Active power of the lamp (and uncertainty)
9	Sampling rate (kHz) (P_{st}^{LM} / SVM)
10	Measurement duration(s) (P_{st}^{LM} / SVM)
11	Optical waveform data (Instructions in Results Report form)
12	Dominant frequency (optional)
13	Modulation depth (optional)
14	Ambient temperature (and uncertainty)

Table 5. Laboratory information to be reported

	Other information reported
15	TLM measurement device used (manufacturer and model, or description)
16	Optical input method (sphere or bench)
17	Power supply and AC power meter used (manufacturer and model)

5 Assigned Values

Assigned values are determined for the purpose of proficiency test, and in IC 2023, this applies to measurements of P_{st}^{LM} and SVM for the lamp artefacts (ART-1 to ART-4). The assigned values in IC 2023 are given from the reference values determined in the Nucleus Laboratory Comparison (NLC), the details of which are described in section 6.

The IC 2023 will be conducted as a star-type comparison between the Operational Nucleus Laboratory (KIEL) and each of a number of participant laboratories. The set of lamp artefacts (ART-1 to ART-4) will be sent from the Operational Nucleus Laboratory to each participant laboratory and returned to the Operational Nucleus Laboratory. The artefacts will be measured by the Operational Nucleus Laboratory before and after shipping and measurement by each participant laboratory. The assigned values will be determined from the two Operational Nucleus Laboratory measurements (before and after shipping) with the correction factors described in section 6.2. This calibration of the artefacts will be

undertaken by the Operational Nucleus Laboratory in compliance with the test methods and procedures described in section 10 with evaluation of measurement uncertainties in compliance with accredited and/or peer reviewed procedure and data analysis described in section 13.

NOTE: The linked regional interlaboratory comparisons, EMPIR MetTLM and China GBV-LC TLM are to use the same approach so that their participants' results can be compared with the Assigned Values.

6 Nucleus Laboratory Comparison

6.1 Methods and Procedures

Prior to the IC 2023 measurement rounds, the NLC was conducted to establish equivalence among the Nucleus Laboratories' measurements, to verify the results of the Operational Nucleus Laboratories' measurements of all quantities, and to establish the reference values for the comparison artefacts. The measurements in the NLC used basically the same test methods and procedures described in this Technical Protocol document, except that each laboratory in the NLC measured two artefact sets (each with four LED lamps) as well as one ART-5 unit (waveform generator) which contains five waveform profiles. Each of the two Operational Nucleus Laboratories (KIEL and DTU) served as the pilot laboratory for the NLC, conducting a star-type comparison with two sets of ART-1 to ART-4 (KIEL) and a modified star-type comparison with ART-5 (DTU) with the other Nucleus Laboratories and the Link Laboratories.

While some measurement conditions (sampling rate, measurement duration, use of low-pass filters) are left open for each participant to choose in IC 2023 (within the range recommended by the IEC standards and CIE TN012), Nucleus Laboratories investigated the effects of these parameters and chose the set of the values that are considered to produce consistent results. The choice of optical geometry (sphere or bench) is left up to each Nucleus Laboratory. The details of these will be reported in the IC 2023 Final Report.

If the results of the Nucleus Laboratories measurements agreed within acceptable variations for a quantity of an artefact, the measurements of the Operational Nucleus Laboratory stand as the reference values for IC 2023, and the measurements of the Link Laboratories stand as the reference values for the linked regional comparisons. In the cases where the measurement variations are significant, the weighted mean or simple mean, as determined appropriate, of all the Nucleus Laboratories' results are calculated to establish the refence values (assigned values in section 5) and then correction factors for the Operational Nucleus Laboratory and all the Link Laboratories for each quantity and each artefact. Thus, the corrected values of each of these laboratories represent the reference value, with which the results of the regional comparisons can be linked to those of IC 2023.

Two artefact sets (total eight lamps) were measured by each laboratory in the NLC to ensure reliability of the comparison results for each laboratory. The correction factors for each quantity of each artefact type are obtained as an average from the measurement of the two artefacts.

Five laboratories were involved in the NLC. KIEL was the pilot laboratory for the lamp artefacts, and DTU, NIST, NLTC and EVERFINE are called 'participants' hereinafter. There were four bilateral comparisons between the pilot and four participants with two artefact sets of lamps for each participant. Each set consists of four LED lamps (ART-1,2,3,4). The pilot laboratory first measured all the artefacts, shipped two artefact sets to each participant. The participants measured the two sets and shipped them back to the pilot laboratory where they were measured again. The four bilateral comparisons were carried out simultaneously to save time. The two measurements (before and after) by the pilot laboratory verified the stability of the artefacts during the NLC, including transportation.

The comparison of ART-5 was conducted separately, with DTU as the pilot laboratory. Two ART-5 units were used for two bilateral round robin comparisons each between the pilot and two of the participants (round robin 1: DTU → KIEL → NIST → DTU and round robin 2: DTU → NLTC → EVERFINE → DTU).

6.2 Data Analysis

The analyses are conducted following the model from Key Comparison analysis by Consultative Committee for Photometry and Radiometry (CCPR, 2019). The analysis steps below are for each artefact type (ART-1,2,3,4). Absolute difference, rather than relative difference (in %), is used in the analysis, as both P_{st}^{LM} and SVM can have a value of zero or very close to zero. ART-5 is for technical study and is analysed separately.

Symbol $x_{i,j}$ represents a value of either P_{st}^{LM} or SVM for lamp j (j=1 to 2) of each artefact type measured by participant i (i=1 to 4), where i=1 to 3 are the participants that serve as Supporting Nucleus Laboratories and i=4 is the participant that serves only as a link laboratory. The two measurements by the pilot laboratory are denoted $x_{i,j,\mathrm{b}}^{\mathrm{P}}$ and $x_{i,j,\mathrm{a}}^{\mathrm{P}}$ for before and after the measurement by participant i, for lamp j, respectively, for the artefact sent to participant i.

First the results of the pilot's two measurements (before and after) for each lamp are averaged:

$$x_{i,j}^{\mathrm{P}} = (x_{i,j,\mathrm{a}}^{\mathrm{P}} + x_{i,j,\mathrm{b}}^{\mathrm{P}})/2 \quad (1)$$

The uncertainty for artefact stability during each bilateral comparison (converted from a rectangular distribution to standard uncertainty) is evaluated as

$$u_{\mathrm{stab},i,j} = (x^{\mathrm{P}}_{i,j,\mathrm{a}} - x^{\mathrm{P}}_{i,j,\mathrm{b}})/(2\sqrt{3}) \tag{2}$$

Then the difference $\Delta_{i,j}$ between measurement of each lamp by participant i and the pilot laboratory is calculated,

$$\Delta_{i,j} = x_{i,j} - x^{\mathrm{P}}_{i,j} \tag{3}$$

For pilot laboratory, i=0 is used hereinafter, and $\Delta_{0,j}$=0.

With the uncertainty $u(x_i)$ of measurement reported by each participant i and the reproducibility $u_{\mathrm{rep}}(x_0)$ of the pilot laboratory, the uncertainty $u(\Delta_{i,j})$ of the difference $\Delta_{i,j}$ is estimated by

$$u(\Delta_{i,j}) = \left[u^2_{\mathrm{rep}}(x_0) + u^2(x_i) + u^2{}_{\mathrm{stab},i,j}\right]^{\frac{1}{2}} \tag{4}$$

Note that, if the difference between the two measurements (before and after) by the pilot laboratory is larger, the value of $u(\Delta_{i,j})$ will be larger, this lamp result will be less weighted in the calculation of the reference value in eq. (6).

For the pilot laboratory, $u(\Delta_{0,j})$ is given by

$$u(\Delta_{0,j}) = \left[u^2_{\mathrm{rep}}(x_0) + u^2(x_0)\right]^{\frac{1}{2}} \tag{5}$$

where $u(x_0)$ is the uncertainty of pilot laboratory measurements $x^{\mathrm{P}}_{i,j,\mathrm{b}}$ and $x^{\mathrm{P}}_{i,j,\mathrm{a}}$.

The reference value Δ_{ref} is calculated as the weighted mean of $\Delta_{i,j}$(i=0 to 3) for all Supporting Nucleus Laboratories and the pilot laboratory for each artefact type, by

$$\Delta_{\mathrm{ref}} = \sum_{j=1}^{2}\sum_{i=0}^{3} w_{i,j} \cdot \Delta_{i,j} \tag{6}$$

where

$$w_{i,j} = u^{-2}(\Delta_{i,j}) \Big/ \sum_{j=1}^{2}\sum_{i=0}^{3} u^{-2}(\Delta_{i,j}) \tag{7}$$

The standard uncertainty of the reference value is calculated from one set of $u(\Delta_i)$ (average of $u(\Delta_{i,1})$ and $u(\Delta_{i,2})$), as the participants' measurements on two lamps (for each artefact type) are nearly fully correlated. But it is assumed there is no correlation between participants, then the uncertainty of Δ_{ref} is calculated as

$$u(\Delta_{\mathrm{ref}}) = \left[\sum_{i=0}^{3} u^{-2}(\Delta_i)\right]^{-\frac{1}{2}} \tag{8}$$

If the uncertainties reported by all the participants do not appear to be consistent with the variations in the results for each quantity, simple mean of all labs' results may be used as the reference value. In this case, instead of eq. (6),

$$\Delta_{\mathrm{ref}} = \frac{1}{8}\sum_{j=1}^{2}\sum_{i=0}^{3}\Delta_{i,j} \tag{9}$$

The uncertainty of Δ_{ref} in this case, instead of eq. (8),

$$u(\Delta_{\mathrm{ref}}) = \frac{1}{4}\left[\sum_{i=0}^{3} u^{2}(\Delta_i)\right]^{\frac{1}{2}} \tag{10}$$

The bias, b_i, of each participant i and the pilot laboratory (i=0) for each artefact type is given by

$$b_i = \Delta_i - \Delta_{\mathrm{ref}} \tag{11}$$

The correction factor c_i for each participant i (some of them serve as Link Laboratories for regional comparisons) and the pilot laboratory (i=0), for each artefact type, is given by,

$$c_i = \Delta_{\mathrm{ref}} - \Delta_i \tag{12}$$

and for the pilot laboratory (Operational Nucleus Lab),

$$c_0 = \Delta_{\mathrm{ref}} \tag{13}$$

The correction factor c_0 or c_i is subtracted from the result of Operational Nucleus Laboratory or of the Link Laboratories to bring their results to be equal to the reference value. The results of the comparison and the derived correction factors will be reported in the NLC report.

7 Testing Period and Shipping Instructions

The measurement rounds for IC 2023 will start in October of 2023 and are expected to be completed by the end of January 2024. There may be two or three sequential measurement rounds depending on the number of participants.

After the participant has been accepted to IC 2023 and paid the corresponding fee, the participant will be contacted and informed when the artefact set ART-1 to ART-4 will be shipped from KIEL, the Operational Nucleus Laboratory. If the participant also selected the optional technical study using a waveform generator (ART-5), this will be sent from DTU, the Operational Nucleus Laboratory for ART-5.

7.1 Procedures for ART-1 to ART-4

Upon receiving the lamp comparison artefacts (ART-1, ART-2, ART-3 and ART-4), the participant shall inform KIEL, the Operational Nucleus Laboratory immediately, upon which time the participating laboratory will be informed of the deadline for testing the artefact set. The artefacts are fragile and will be transported in a robust transport case. The artefacts shall be stored at room temperature between 15°C and 35°C and relative humidity less than 75%.

The participant has two weeks from the date of receipt of the artefact set to complete the measurements and report results to the Operational Nucleus Laboratory. If the results are not received by the deadline date, the laboratory will be disqualified. In case of a problem, the participant should inform the Operational Nucleus Laboratory before the deadline, so that a solution can be determined.

After the results are received by the Operational Nucleus Laboratory, the participant will receive instructions for return shipping. Upon receiving those instructions, the participant must promptly ship the artefacts back to the Operational Nucleus Laboratory. The same transport case should be used, and the packing instructions provided should be followed.

7.2 Procedures for ART-5

Upon receiving the artefact, the participant shall inform DTU, the Operational Nucleus Laboratory for ART-5 immediately, upon which time the participating laboratory will be informed of the deadline for testing the artefact. ART-5 is fragile and will be transported in a robust transport case. ART-5 shall be stored at room temperature between 15°C and 35°C and relative humidity less than 75%.

The participant has one week from the date of receipt of ART-5 to complete the measurements and report results to the Operational Nucleus Laboratory. If the results are not received by the deadline date, the laboratory will be disqualified. In case of a problem, the participant should inform the Operational Nucleus Laboratory before the deadline, so that a solution can be determined.

After the results are received by the Operational Nucleus Laboratory, the participant will receive instructions for return shipping. Upon receiving those instructions, the participant must promptly ship ART-5 back to the Operational Nucleus Laboratory. The same transport case should be used, and the packing instructions provided should be followed.

8 Initial Check

If anything is unclear about any of the documents, this must be reported immediately to the technical contact of the Operational Nucleus Laboratory. On arrival, each artefact in the set should be inspected for damage and tested for proper operation. If any problems are found, the participating laboratory should immediately contact the Operational Nucleus Laboratory in order to receive a replacement artefact or artefact set.

The artefacts used in this IC test shall not be modified, adjusted, or used for any purpose other than that described in this document.

The Operational Nucleus Laboratory will make an assessment of any drift in performance (difference between the before and after measurements made by the Operational Nucleus Lab) of the artefacts during the comparison. This will be based on their measurements before shipment and after their return. If considerable drift is found, this will be taken into account in the evaluation of the comparison. If the observed drift has exceeded 0.8 x SDPA (see section 13.3) for P_{st}^{LM} or SVM, the relevant results for that artefact will be discarded and a replacement artefact will be sent to the participant laboratory for re-measurement.

9 Measurement Geometry

The artefacts shall be operated in an integrating sphere or on an optical bench where any ambient lights are completely shielded from the TLM measurement instrument. In either measurement system, the LED lamp artefacts shall be mounted in the operational orientation specified in section 10.2.

10 Test Methods and Procedures

10.1 General

The participating laboratory shall use the measurement methods described in IEC TR 61547-1 (IEC, 2020) for P_{st}^{LM} and IEC TR 63158 (IEC, 2018) for SVM, and should also comply with recommendations in CIE TN 012 (CIE, 2021) for both quantities.

The IC 2023 will be conducted as a star-type comparison between the Operational Nucleus Laboratory (KIEL) and each of a number of participant laboratories. The set of lamp artefacts (ART-1 to ART-4) will be sent from the Operational Nucleus Laboratory to each participant laboratory and returned to the Operational Nucleus Laboratory. The artefacts will be measured by the Operational Nucleus Laboratory before and after shipping and measurement by each participant laboratory.

In the optional technical study using the waveform generator (ART-5), the comparison will be conducted as a modified star-type comparison between the Operational Nucleus Laboratory (DTU) and the participants. The artefact will be measured by the Operational Nucleus Lab before and after shipping and measurement by two (or maximum three) participant laboratories.

The participating laboratory may perform one measurement or repeated measurements for each artefact with their TLM instrument, depending on their normal testing practice. Regardless of how the measurements are conducted, participating laboratories will report one set of results (e.g., the average in case of repeated measurements). Repeated measurements (typically three measurements of each artefact) may provide the Type A component of uncertainties for each artefact if it is needed.

The Operational Nucleus Laboratories will perform one measurement of each artefact (except when any problem is observed) for each measurement round because the reproducibility of measurements of all artefacts has been tested in advance by the Operational Nucleus Laboratory to evaluate the Type A component of uncertainty.

The participating laboratory shall not age or season the artefacts, and should keep the operating time of all the artefacts to a minimum.

10.2 Mounting DUT

All LED lamps (ART-1, ART-2, ART-3 and ART-4) shall be operated in base-up position and air circulation around the artefacts should be kept to a minimum.

ART-4 lamp has three modes of operation and shall be measured only in the *first mode* when initially turned on, where only the white LEDs are on and the red LEDs are off. The other modes on this lamp are selected by (quickly) turning the lamp off and back on again, however these other modes are not part of IC 2023.

ART-5 (if participant selects this option) shall be placed in normal horizontal orientation.

10.3 Environmental Conditions

The ambient temperature shall be 25°C ± 5°C and the laboratory shall report the temperature reading during the TLM measurement and the uncertainty of that temperature measurement.

10.4 Electrical Operation

All LED lamps (ART-1, ART-2, ART-3 and ART-4) shall be operated by setting the supply voltage to the rated value as given below.

230 VAC, 50 Hz

The supply voltage reading shall be within ± 0.5 % from the rated voltage, and must be measured at (or very close to) the supply terminals of DUT. Report the measured supply voltage and the uncertainty of measurement. The supply voltage of ART-5 (if used) can be in the voltage range specified by the manufacturer.

To operate the LED lamps, an AC power supply and AC power meter that meet requirements in CIE S 025 (CIE, 2015) or equivalent EN 13032-4 (EN, 2015) (section 4.3.2 and 4.3.3 of CIE S 025) shall be used (power supply THD ≤1.5%, power meter bandwidth ≥100 kHz – see section 4.3.3.2 of CIE S 025).

NOTE: In China GBV-LC TLM comparison, GB/T 39394 (China GB, 2020), which is equivalent to CIE S 025, may be used instead of CIE S 025.

10.5 Stabilisation of DUT

All artefact LED lamps (and ART-5 if used) shall be stabilised for 15 minutes (from cold start of the lamp) before starting the measurements of TLM quantities and electrical quantities. The Nucleus Laboratories have determined that this is sufficient time for stabilisation of the selected artefacts.

11 Uncertainty Reporting by the Participants

Uncertainty statements in all the measurement results are requested in IC 2023, and they are required if the results are to be used as a Proficiency Test (PT). The uncertainty of each measured quantity shall be expressed in expanded uncertainty with a confidence interval of 95% or a coverage factor k=2 (see JCGM, 2008). The uncertainty for each measurement result shall be expressed as absolute values of P_{st}^{LM} or SVM (not relative in %). If some participants do not report the uncertainties, their results will still be accepted (however E_n numbers will not be reported for them).

12 Reporting by the Participants

Report the results using the Results Report Form (an Excel spreadsheet provided by the Operational Nucleus Laboratory at the start of their measurement round). After measurements are complete, participants must submit results to the Operational Nucleus Laboratory by the stated deadline (*i.e.*, two weeks from receiving the artefacts).

Participants are also required to submit the waveform data in *.csv (comma separated value format), and where possible using the file structure presented in CIE TN 012. Participants will be issued with a link to a secure cloud-based server where they can upload their waveform data.

Each participant will be asked to submit a brief description of their TLM measurement system together with photos of the TLM measurement instrument and test setup (with one of the artefact lamps mounted) in the Results Report Form.

13 Data Analysis

13.1 Reference values for each artefact

The Operational Nucleus Laboratory will undertake the role of the reference laboratory for IC 2023. The Reference values for the IC 2023 measurement rounds will be determined for each quantity of each artefact from the measurements by the Operational Nucleus Laboratory (with corrections determined by the NLC if applicable).

The reference value, X, of each quantity for each artefact is determined from the reference laboratory measurement, x_0, using the correction factor, c_0, (determined from the NLC – see section 6) as:

$$X = x_0 - c_0 \tag{14}$$

The uncertainties of the reference values are calculated by:

$$u(X) = \left[u^2(\Delta_{\text{ref}}) + u_{\text{rep}}^2(x_0)\right]^{\frac{1}{2}} \tag{15}$$

where $u(\Delta_{\text{ref}})$ is from eq. (8) or eq. (10), and $u_{\text{rep}}(x_0)$ is the reproducibility of the measurements of the reference laboratory during the IC 2023 measurement rounds.

This approach will, in principle, force the measurement results by the Operational Nucleus Laboratory to be equal to the reference value determined by the NLC, and all participants' results in IC 2023 will be compared to this reference value. The reference values for P_{st}^{LM} and SVM will be the assigned values (section 5) for the purpose of proficiency test.

13.2 Differences from reference value

All the results of the participants will be compared with the reference values for each artefact as determined by the Operational Nucleus Laboratory.

The results will be presented as differences between the participant's results, x, and the reference value, X, in absolute values of P_{st}^{LM}, SVM, and other quantities.

13.3 z' score and E_n number

The criteria used to analyse and evaluate the performance of participating laboratories are given by the z' score (ISO, 2022) and the E_n number (ISO/IEC, 2010). The E_n numbers and z' scores are calculated only for the measurement quantities listed in Table 2 (P_{st}^{LM} and SVM).

The z' score is calculated for all results, and is calculated by:

$$z' = \frac{x - X}{\sqrt{\hat{\sigma} + u_X^2 + u_{\text{drift}}^2}} \tag{16}$$

where $\hat{\sigma}$ is the SDPA value (Standard Deviation for Proficiency Assessment) which, in IC 2023 is the generic standard uncertainty of a participant's measurement. The SDPA values for each comparison quantity is estimated from the results of the Nucleus Laboratory Comparison and will be published in the Nucleus Laboratory Comparison Report.

The u_X is the standard uncertainty of the assigned value, which is equal to $u(X)$ in eq. (12). The u_{drift} is the uncertainty contribution from the expected artefact drifts (controlled to within 0.8 x SDPA, see section 8), calculated by:

(17)

$$u_{\text{drift}} = \frac{0.8 \cdot \hat{\sigma}}{2\sqrt{3}}$$

The values of $\hat{\sigma}$ and u_X will be listed in the Nucleus Laboratory Comparison Report, which will be published before the start of the first round of IC 2023 measurements.

E_n numbers are calculated, where the uncertainties of measurements are reported by the participant, according to

$$E_n = \frac{x - X}{\sqrt{U_{\text{lab}}^2 + U_{\text{ref}}^2}} \tag{18}$$

where:

x: value measured by a participant
X: assigned value (average of corrected Operational Nucleus Laboratory measurements, before and after)
U_{lab}: expanded uncertainty (k=2) of a participant's result
U_{ref}: expanded uncertainty (k=2) of the assigned *value*

U_{ref} is calculated by:

$$u_{\text{ref}} = \left[\left(\frac{u_1 + u_2}{2}\right)^2 + \frac{(X_1 - X_2)^2}{\left(2\sqrt{3}\right)^2}\right]^{\frac{1}{2}} \tag{19}$$

And

$$U_{\text{ref}} = 2\, u_{\text{ref}}$$

where X_1 and X_2 are measured values by the Operational Nucleus laboratory, before and after the participant's measurement, and u_1 and u_2 are their standard uncertainties. The equation assumes that the two measurements are fully correlated. The second term in the square root is the standard uncertainty associated with the drift of the artefacts as measured by the Nucleus laboratory (taken as a rectangular distribution).

13.4 Interpretation of *z'* score and E_n number

If a value of $|E_n|$ is equal to or smaller than 1.0, this is generally satisfactory. If a value of $|E_n|$ is greater than > 1.0, this is generally considered unsatisfactory.

If the value of $|z'|$ is equal to or smaller than 1.0, this is generally considered satisfactory. The value of 2.0 < $|z'|$ < 3.0 is considered to be questionable, and $|z'|$ ≥ 3.0 is generally considered to be unsatisfactory, but the judgment as to whether the result is acceptable will

depend on the relevant accreditation bodies. The E_n numbers (if available) and the z' scores of all participants will be reported in the interim and final reports in the event that they might be used by the accreditation bodies.

The use of E_n numbers or z' scores or both will be up to the accreditation bodies (it also depends on which test method they refer to), but note that, if an E_n number is used, participant's reported uncertainties affect the E_n numbers and thus judgment for the competence of the laboratory applying for accreditation. Currently, testing labs' uncertainties are not used in many conformity assessment programmes. On the other hand, z' score is directly based on deviation of their results and more commonly used in conformity assessment of product testing.

14 Reporting to the Participants

14.1 Individual Test Report (ITR)

The participants will receive an Individual Test Report (ITR) within two months from the time their test results are received by the Operational Nucleus Laboratory. The ITR will show the results measured by the participants on all the artefacts and quantities, compared with the assigned values determined by the Operational Nucleus Laboratory, including associated uncertainties when available.

The ITR will also include E_n numbers and z' scores of the quantities listed in Table 2. ITRs are kept strictly confidential in IEA 4E SSL Annex. The participant shall also keep the information on the assigned values confidential until all rounds are finished. The participants may submit the ITR as evidence of their competence to an accreditation body or the regulatory authority under the confidentiality stated in section 15.

14.2 Final Report

After all measurement rounds are completed, a Final Report showing the results of all participants and various analyses will be published. The participants' results will be de-identified and expressed using random laboratory codes. Only the participant will be informed which code corresponds to their laboratory. If a participant would wish for their name and city, country where the laboratory is located to appear in the list of participants (which is **not** linked to the laboratory code used in the report) in Final Report, it will be included under their agreement.

The measurement results will be evaluated on the basis of the participants' results, the statistical calculations and the assigned values. The findings of this evaluation will be presented in the final report, namely:

A. For each measurement point, for each participant:
   - The reference value and its expanded uncertainties (U)
   - SDPA value
   - The results of the participant and their expanded uncertainties (U)
   - The E_n number and z' score of the participant
   - A graphic representation of some typical measurement results from the laboratories, including the uncertainty limits

B. The report can also describe the following components:
   - Overview of cited documents, guidelines and publications
   - If necessary, a description of the measurement methods and equipment used by the participants
   - A description will also be provided of the applied statistics
   - Technical derivation and Uncertainty Budget of SDPA
   - Evaluation of the test methods and used in this IC
   - General recommendations, statistics, etc.
   - Conclusions

The statistical analysis of the participants' results will take place in compliance with international standard, ISO 13528.

If a participant wishes to appeal on the evaluation of results presented in any of the reports, they should contact the appropriate IC 2023 Operational Nucleus Laboratory.

15 Confidentiality

The identity of the ITRs for each participant shall remain confidential. The files containing the results, reports and other material relating to the Interlaboratory Comparison scheme will be stored in secure folders and locked cabinets or electronically in a secured computer that are only accessible to the Operational Nucleus Laboratory and IC 2023 management team.

The laboratories will be identified by a laboratory code comprised of at least three characters, such as L01...LXX. This laboratory code will be unique to each participant and will only be known to the Operational Nucleus Laboratory and IC 2023 management team.

To enable efficient dialogue around the processing and analysis of the test results, participants may choose to waive confidentiality. However, confidentiality will always be maintained in the final report and in any communication with the outside world.

Furthermore, as discussed in Section 3, the artefacts' ID numbers will be re-numbered when they are re-used in subsequent measurement rounds so that there is no possibility that participants of later rounds may gain advantage from early disclosure.

16 Eligibility of Participation and Fee

Laboratories that have measurement equipment that is capable of conducting measurements of P_{st}^{LM} defined in IEC TR 61547-1 and SVM defined in IEC TR 63158 are eligible to participate. Participants are officially accepted only after receipt of the fee payment. Participants from the member countries of IEA 4E SSL Annex (i.e., Australia, Denmark, France, Korea, Sweden and the United Kingdom) will have a discount in the fee. The fees for participating in IC 2023 are available on the SSL Annex IC 2023 webpage.

17 References

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Annex 1. Artefact Selection – Stabilisation Test Protocol

This annex provides information on how the IC2023 management team selected the comparison artefact LED lamps by conducting stability tests.

A.1 Test Procedures

A.1.1 Seasoning

- All the sample LED lamps will be seasoned for 24 hours.

A.1.2 Laboratory and environmental conditions

- The sample LED lamps shall be operated in an integrating sphere or on an optical bench where any ambient lights are completely shielded from the TLM instrument.
- All sample LED lamps shall be operated in base-up position and drafts should be minimised.
- The ambient temperature shall be 25°C ± 5 °C and report the temperature reading during TLM measurement and the uncertainty of temperature measurement.

A.1.3 Electrical test conditions and electrical equipment

- All sample LED lamps shall be operated with supply voltage of 230 V AC, 50 Hz with a THDv ≤1.5%.
- The supply voltage reading must be measured at (or very close to) the supply terminals of DUT and shall be within ± 0.5 % of 230 V AC.
- The AC power meter power meter shall have a bandwidth ≥100 kHz and meet requirements in CIE S 025 (section 4.3.2 and 4.3.3).

A.1.4 Measurement of photometric and electrical quantities

- The duration for stability test will be 63 minutes (3,780 seconds as shown below) of continuous operation of the lamp.
- As close as possible to startup of the sample LED lamp and repeated at 5 minute intervals, for a total of 13 measurements per lamp:
  1. acquire the TLM waveform(s) for deriving SVM (5 s) and P_{st}^{LM} (180 s), and measure:
  2. lamp supply current and/or active power
  3. relative luminous intensity or relative total luminous flux

Measurement Sequence

Measurement Number:	#1 (5 minutes)				#2 (5 minutes)				[...]	#13 (3 minutes)		
Elapsed time (seconds):	0	1-5	6-180	181-299	300	301-305	306-480	481-599	[...]	3600	3601-3605	3606-3780
Lamp remains on:												
Relative luminous flux/intensity, current/active power:									[...]			
SVM TLM waveform:												
P_{st}^{LM} TLM waveform:												

The TLM waveform may be recorded as a continuous waveform from start (0 min) to completion of test (63 min).

A.2 Analysis of Stability

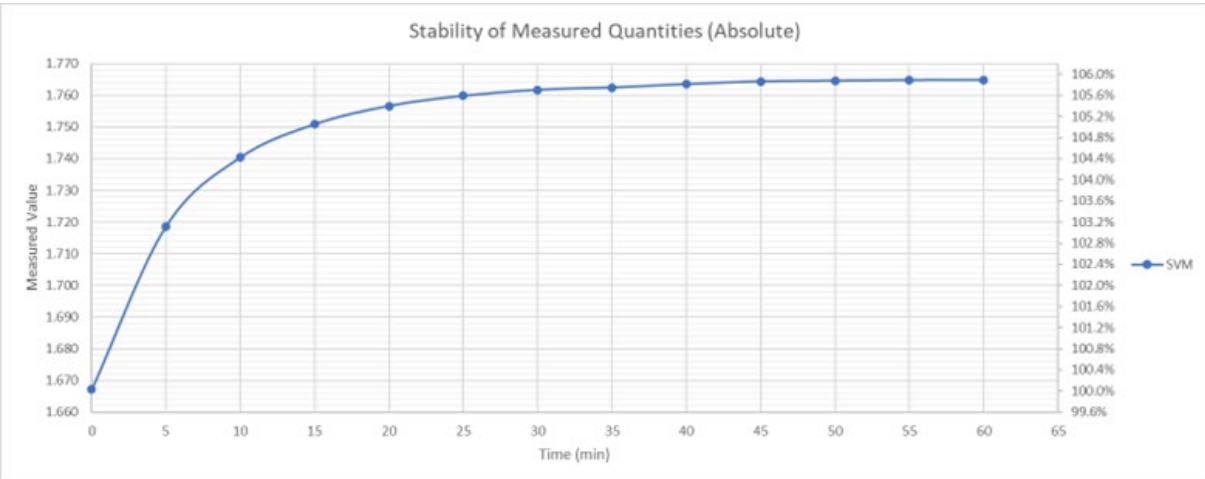
Each sample's measurements are to be analysed by plotting time-based graphs in the formats similar to the following. Illustrative examples are included.

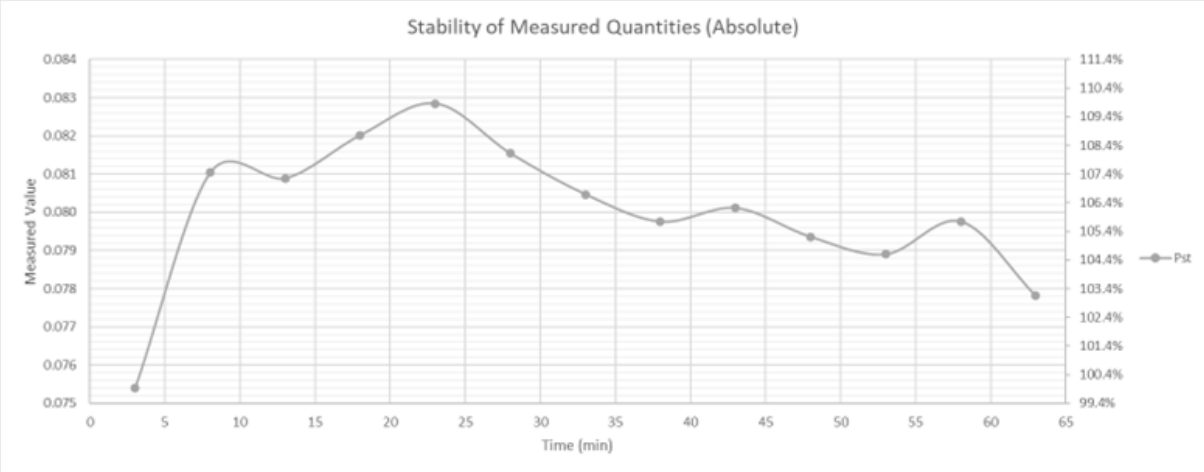
A.2.1 Absolute values versus time

Separate graphs of the quantities vs time for:

- Relative luminous flux (or intensity)
- Relative supply current (or active power) – absolute scale on secondary axis (right hand side)
- Absolute SVM – relative scale on secondary axis (right hand side)
- Absolute P_{st}^{LM} – relative scale on secondary axis (right hand side)

Note: relative measures normalised to initial value

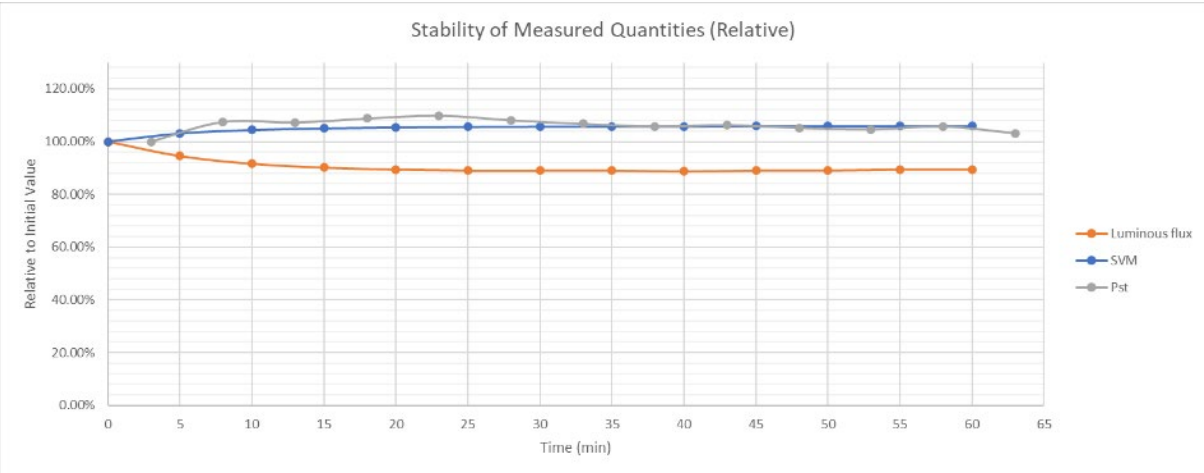




A.2.2 Relative values of multiple quantities versus time

Combined graph of the relative quantities (normalised to initial values) versus time for:

- Luminous flux (or intensity)
- Supply current (or active power)
- SVM
- P_{st}^{LM}

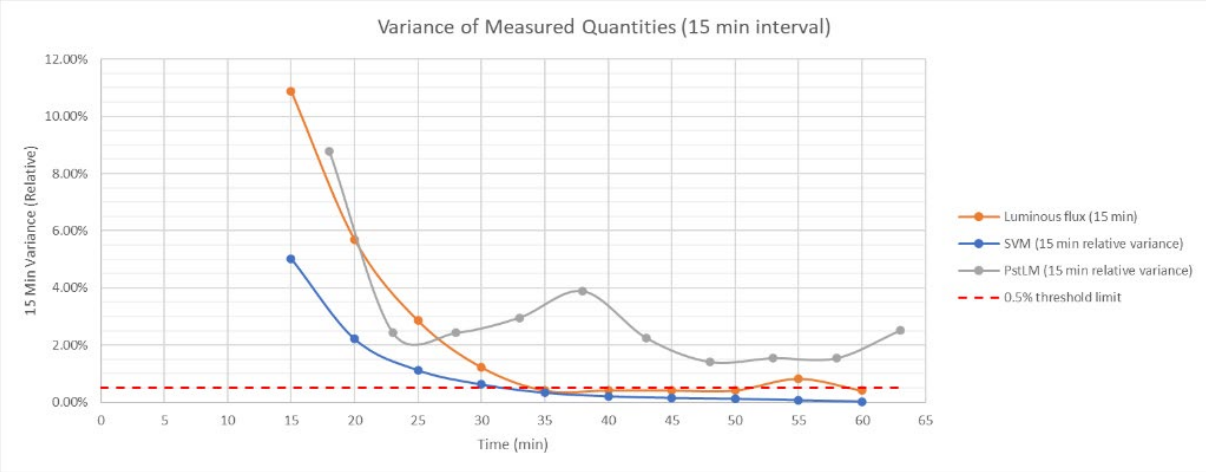


A.2.3 Fifteen-minute variance of relative values versus time

Combined graph of rolling 15-minute variances of the calculated values of quantities versus time for:

- Luminous flux (or intensity)
- Supply current (or active power)
- SVM
- P_{st}^{LM}

Note: the graph is to include a threshold line nominally at 0.5% (for inspection as per CIE S 025 Cl 4.4.1). Note: this threshold may be adjusted upward depending absolute levels.



A.2.4 Fifteen-minute variance of absolute values versus time

For very low SVM and P_{st}^{LM} measured values the relative variance may present as very high. In these situations, plot SVM and P_{st}^{LM} absolute variance (in separate graphs) on a secondary axis instead. Also display an absolute threshold of 0.005 (equivalent to 0.5% of value of 1). Note: absolute threshold may be revised.