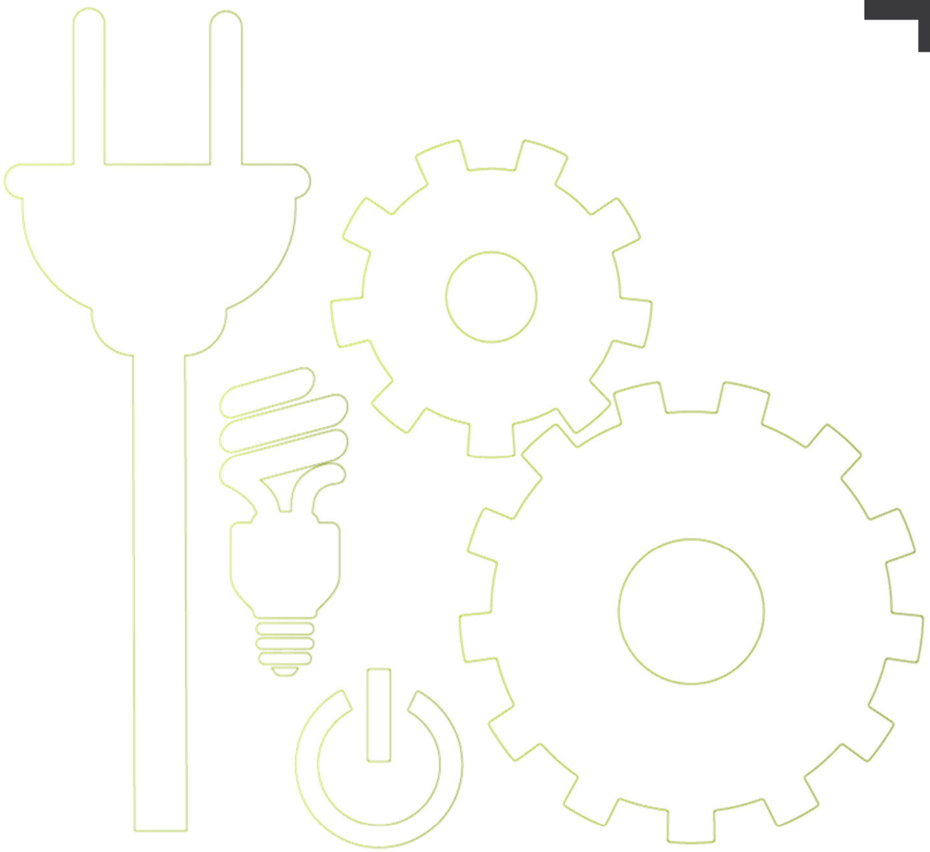
Energy Efficient End-use Equipment
International Energy Agency



Solid State Lighting Annex: 2013 Interlaboratory Comparison

FINAL REPORT

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

SSL Annex Task 2 and Task 3

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Solid State Lighting Annex 2013 Interlaboratory Comparison Final Report

This report was prepared by International Energy Agency 4E Solid State Lighting Annex Task 2 and Task 3.

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Abstract:

This Interlaboratory Comparison (IC 2013) for the measurement of solid state lighting (SSL) products was conducted by International Energy Agency (IEA) 4E SSL Annex between October 2012 and August 2013. Fifty-four laboratories from 18 countries participated in this comparison for measurements of photometric, colorimetric, and electrical quantities of several different types of SSL products. In addition, measurement data from the proficiency testing of 35 laboratories in the National Voluntary Laboratory Accreditation Program (NVLAP) Energy Efficient Lighting Products for SSL and in the National Institute of Standards and Technology's Measurement Assurance Program are linked to IC 2013. And, data from further 21 laboratories from the Asia Pacific Laboratory Accreditation Cooperation (APLAC) proficiency test T088, are also linked to IC 2013, making it a comparison of test results from 110 laboratories and 123 sets of data. Measurements of luminous flux, luminous efficacy, active power, RMS current, power factor, chromaticity *x, y*, correlated colour temperature, and colour rendering index were compared. IC 2013 was also designed so that the results can be recognised as proficiency testing for SSL testing laboratory accreditation programmes worldwide. The differences of participants results from the reference values as well as z' scores (defined in ISO 13528) and E_n numbers (defined in ISO 13528 and ISO/IEC 17043) are all presented, and problems and findings observed from the results are discussed.

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 programs for SSL lighting. This international collaboration brings together the governments of Australia, Denmark, France, Japan, The Netherlands, Republic of Korea, Sweden, United Kingdom and United States of America. China works as an expert member of the 4E SSL Annex. The SSL Annex closed its first term in June 2014 and started on its second five-year term in July 2014. This report is part of the final reporting from the Annex's first term. Further information on the 4E SSL Annex is available from: http://ssl.iea-4e.org/

About the IEA Implementing Agreement on Energy Efficient End-Use Equipment (4E)

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:

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

Current members of 4E are: Australia, Austria, Canada, Denmark, France, Japan, Korea, Netherlands, Switzerland, Sweden, UK and USA. Further information on the 4E Implementing Agreement is available from: www.iea-4e.org

Executive Summary

The Solid-State Lighting (SSL) Annex was established in 2010 under the framework of the International Energy Agency's (IEA) Energy Efficient End-Use Equipment (4E) Implementing Agreement. The IEA 4E SSL Annex (simply "SSL Annex" hereafter) works to assist governments of member countries in promoting SSL as an effective means to reduce energy consumption worldwide. The SSL Annex works internationally to develop tools and recommendations and exchange information to promote harmonised regulations and government programmes addressing challenges with SSL technologies.

Starting in 2011, the SSL Annex launched an initiative that sought to address the lack of a global laboratory performance assessment scheme. This initiative was designed to help support harmonisation of SSL testing around the world by developing an approach to compare and assess the measurement capabilities of testing laboratories, and support accreditation programs for testing laboratories measuring LED lighting products. This work of the SSL Annex provides a useful basis for an interlaboratory comparison in the absence of a common global test standard.

For these purposes, Task 2 (SSL Testing) and Task 3 (Accreditation) of SSL Annex jointly developed and conducted an interlaboratory comparison (IC) program, named IC 2013. The IC 2013 was conducted between October 2012 and August 2013. Fifty-four laboratories from 18 countries participated in this study, comparing measurements of photometric, colorimetric, and electrical quantities of several different types of SSL products. In addition, measurement data from the proficiency testing of 35 laboratories in the National Voluntary Laboratory Accreditation Program (NVLAP) Energy Efficient Lighting Products (EELP) for SSL and in the National Institute of Standards and Technology's (NIST) Measurement Assurance Program (MAP) are linked to IC 2013. And data from further 21 laboratories from the Asia Pacific Laboratory Accreditation Cooperation (APLAC) proficiency test T088, are linked to IC 2013, making it a comparison of test results from 110 laboratories and 123 sets of data.

Five different types of artefact were used in this IC; omnidirectional LED lamp, directional LED lamp, low-power-factor LED lamp (≈0.5 on the average), high CCT LED lamp/luminaire, and incandescent lamp operated on AC voltage, with a few optional types. Measurement of luminous flux, luminous efficacy, active power, RMS current, power factor, chromaticity x and y, correlated colour temperature, and colour rendering index were compared. IC 2013 was also designed so that the results could be recognised as proficiency testing for SSL testing accreditation programmes worldwide. The z' scores (defined in ISO 13528) and E_n numbers (defined in ISO 13528 and ISO/IEC 17043) were evaluated as criteria for use by accreditation bodies. IC 2013 has been recognised so far by National Voluntary Laboratory Accreditation Program (NVLAP) in USA, International Accreditation Japan (IA-Japan), China National Accreditation Service of Conformity Assessment (CNAS, China), Korea Laboratory Accreditation Scheme (KOLAS), and International Accreditation New Zealand (IANZ), and is expected to be recognised by more accreditation bodies.

IC 2013 provided experience in PT on the measurement of SSL products, which supports SSL regulations and government programmes, and also provided useful technical findings for the SSL community. The results for total luminous flux and chromaticity x, y showed that the artefacts measured by most of the laboratories agreed to within ± 5 % in luminous flux and within ± 0.005 in x, y, overall for all artefact types, which are at expected levels of agreement. These results verified the levels of uncertainty of measurements by laboratories using a well-established test method, and that the test method compiled for the IC 2013 was effective in limiting measurement variations. On the other hand, a few extremely large deviations in results were observed, up to 30 % in luminous flux or up to 0.2 in chromaticity x, y for each artefact type. These extreme test results must be caused by some major flaws at the participant laboratories in meeting the requirements in the test method. Identifying these large deviations by some laboratories demonstrates the importance of proficiency testing, as these laboratories would not have become aware of their problems without participating in such an interlaboratory comparison.

The electrical measurement results also identified some issues. The variations in measured RMS current for LED lamps were primarily within ± 3 % (omnidirectional lamp) to ± 15 % (low power-factor lamp), with some deviations much larger than expected (up to 38 %), resulting in many high values of z' score and E_n number. This result indicates that the generic uncertainty and the participants' reported uncertainties for RMS current were significantly underestimated. However, looking at the results of luminous flux and chromaticity for low-power factor lamps, the effect of the RMS current variations on photometric and colorimetric values was found not significant, and thus it would appear that agreement in measured RMS current is not very critical. This is explained by the finding that deviations in RMS current were strongly correlated with power factor in the direction to cancel the changes in active power, though not all the cases. The variations in measured power factor were also larger than expected, mostly within ± 0.02 to ± 0.1 depending on the artefact type. These large variations in the electrical measurements may be caused by differences in the characteristics of the AC power supplies used by the participants, in particular, their output impedance. This is one of the remaining issues for the test methods in use today for LED lighting products, and future improvements are expected.

The uncertainties reported by the participants were found to be in a very large range (often more than two orders of magnitude), and were often significantly underestimated. Some laboratories reported unreasonably small uncertainties (e.g., 0.0001 in chromaticity *x, y*) or unreasonably large uncertainties (e.g., 10 % in luminous flux or 0.02 in chromaticity *x, y*). Several laboratories (not those linked) did not report uncertainties at all or did not report uncertainty of any colour quantities (i.e., chromaticity *x, y*, CCT, CRI). From these findings, it would appear that uncertainty evaluation, especially for colour quantities, is still very difficult for the SSL industry, and reported uncertainties are often not reliable. Practical methods and tools for uncertainty evaluation of measurements, as well as educational documents and training for the SSL industry on practical uncertainty evaluation are urgently needed.

In addition to the differences of participants results from the reference values, both z' scores and E_n numbers were calculated in IC 2013 for possible use by accreditation bodies. These results show that some laboratories would pass on E_n number but fail on z' score or vice versa. In particular, there were some cases where laboratories claiming large uncertainties would pass on E_n number though the deviations in their results were very large. Thus, the use of E_n number alone can be problematic when measurement variations need to be limited by the accreditation programme. In practice, the E_n number is suitable for the purpose of assessing the validity of claimed uncertainties (e.g., in *calibration laboratory* accreditation). The z' score is suitable for the purpose of *testing laboratory* accreditation, which examines a laboratory's competence and compliance to a test method which is developed to limit measurement variations as is often required in product certification activities. For laboratory accreditation programmes serving both purposes (i.e., serving for product certification activities as well as certifying the reported uncertainties), the use of the E_n number *and* z' score would be appropriate. In this study, it was found that the E_n number could be problematic where laboratories had difficulty in uncertainty evaluation, as shown in IC 2013 for colour quantities. And, it was found that the z' score could be problematic if the denominator values were not appropriately specified, as was the case of RMS current measurements in this IC. The results of IC 2013 may be utilised for future SSL proficiency testing using z' score or a similar metric.

This IC 2013 was an attempt to establish a common PT for accreditation programmes supporting different regulations and government programmes using different regional test methods. For this purpose, a special test method was needed and developed by the SSL Annex. A solution for international harmonisation of SSL testing and accreditation would be to use one international test method for SSL products, which will be published soon by the International Commission on Illumination (CIE). Countries would then choose whether to harmonise to this test method standard based on their own needs and regulatory requirements, enabling worldwide mutual recognition of SSL product testing and laboratory accreditation.

The IC 2013 provided many laboratories in many countries with new knowledge and experience in PT for the measurement of SSL products. It also established a basis to promote SSL laboratory testing accreditation world-wide in support of regulations and government programmes to further accelerate the development of SSL.

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Acronyms and Abbreviations

4E	Energy Efficient End-use Equipment
A	Amperes
AB	Accreditation Body
AC	Alternating Current
AIST	National Institute of Advanced Industrial Science and Technology (Japan)
APLAC	Asia Pacific Laboratory Accreditation Cooperation
CCT	Correlated Color Temperature
CEN	Comité Européen de Normalisation (European Committee for Standardisation)
CIE	Commission Internationale de l´Eclairage (International Commission on Illumination)
CRI	Color Rendering Index
D	Directional (lamp)
D1	Directional (downlight)
DC	Direct Current
HCCT	High Correlated Color Temperature
Hz	Hertz
IAC	Incandescent Alternating Current (lamp)
IANZ	International Accreditation New Zealand
IC	Interlaboratory Comparison
IDC	Incandescent Direct Current (lamp)
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IES	Illuminating Enginerring Society of North America
ILAC	International Laboratory Accreditation Cooperation
ISO	International Standards Organisation
K	Kelvin
KOLAS	Korea Laboratory Accreditation Scheme
LED	Light Emitting Diode
lm	lumens
LPF	Low Power Factor (lamp)
MAP	Measurement Assurance Program (US)
NCAS	National Accreditation Service of Conformity Assessment (China)
NIST	National Institute of Standards and Technology (US)
NLTC	National Lighting Test Centre (China)
NMI	National Metrology Institute
NMIJ	National Metrology Institute of Japan
NVLAP	National Voluntary Laboratory Accreditation Program
OD	Omni-Directional
PRR	Participants Results Report
PT	Proficiency Testing
RP	Remote Phosphor (lamp)
SDPA	Standard Deviation for Proficiency Assessment
SSL	Solid State Lighting
TL	Tubular Linear (lamp)
USA	United States of America
VSL	Dutch Metrology Institute (The Netherlands)
W	Watt

1 Introduction

A large-scale, international interlaboratory comparison test of solid-state lighting (SSL) products has been conducted under the framework of the Solid State Lighting (SSL) Annex[1], part of the International Energy Agency (IEA) Implementing Agreement on Energy Efficient End-use Equipment (4E)[2]. The SSL Annex is organised to assist country governments promoting quality assurance of LED lighting products world-wide. There are ten countries participating in the SSL Annex[1]. Regulations and government programmes (product certification activities) on LED lighting products are being established in many countries, and one of the urgent needs to support such government activities is to establish laboratory proficiency testing (PT) for testing accreditation programs. Establishing PT, however, is not easy because PT providers are required to have high-level knowledge and experience in measurement of SSL products and also authorisation by accreditation bodies and/or government programmes. Regulators and accreditation bodies also need knowledge of the current state of interlaboratory differences in SSL measurements when determining products specifications. For these purposes, Task 2 (SSL Testing, Leader: Y. Ohno) and Task 3 (Accreditation, Leader: K. Nara) of SSL Annex jointly developed and conducted an interlaboratory comparison (IC) program, named IC 2013.

The IC 2013 was organised to serve as a type of PT for a participant laboratory. Interlaboratory comparisons are known to be one of the most reliable tools to assess the technical competence of a participating laboratory. This programme was organised in compliance to ISO/IEC 17043 [1] to facilitate the use by accreditation bodies (ABs) as described in ILAC P9:11/2010 [2]. The present programme is expected to contribute to the accreditation of laboratories, by which, mutual recognition of the measurement results will be realised to lower technical trade barriers in the present global market.

In order to cover many participating laboratories world-wide, IC 2013 was operated by four Nucleus Laboratories; VSL BV (Dutch Metrology Institute, The Netherlands), National Lighting Test Centre (NLTC, China), National Metrology Institute of Japan - Advanced Industrial Science and Technology (AIST, NMIJ, Japan), and National Institute of Standards and Technology (NIST, USA). The participants were assigned to one of the Nucleus Laboratories so that basically, VSL covered the European region, NLTC covered China and Asia Pacific region, AIST, NMIJ covered Japan, and NIST covered Americas region. The Nucleus laboratories had formally compared test results and established equivalence amongst themselves in advance [3].

The IC 2013 in all regions was conducted in compliance with the SSL Annex IC Generic Protocol [4], which specified the basic five types of comparison artefacts including a few options, eight measurands (electrical, photometric and colorimetric quantities), assigned values, testing period and shipping instructions, measurement procedures, uncertainty calculation, evaluation of performance using z’ score (defined in ISO 13528 [8]) and E_n number (defined in ISO 13528 [8] and ISO/IEC 17043 [1]), reporting, and other details. Each region was allowed to select LED lighting products commonly available in their market for the types of artefact specified in the Generic Protocol. The exact protocols including the specifications of the artefacts used in each region were documented as the *SSL Annex Interlaboratory Comparison Protocol for -VSL, -NLTC, -AIST, NMIJ, and –NIST* (hereinafter called “Regional Protocols”), which were distributed to the participants in each region, and made available to ABs and government agencies on a request basis.

The IC 2013 used a test method, *SSL Annex Interlaboratory Comparison Test Method 1.0* [5], which encompassed all the requirements in the SSL test methods already available in the USA, Japan, China, and

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[1] http://ssl.iea-4e.org/
[2] http://www.iea-4e.org/

also including the draft of the SSL test method being developed jointly by International Commission on Illumination (CIE) and Comité Européen de Normalisation (CEN: European Committee for Standardisation)[3], so that the results could be considered for acceptance by ABs and regulatory programmes world-wide using these regional test methods.

The IC 2013 was launched in October 2012, and measurements were completed in August 2013. The announcement of IC 2013 was made publicly and applications were accepted until April 2013. Registration for participants was open to all laboratories including countries that are not part of the SSL Annex. As a result, 54 laboratories from 18 countries participated in the IC. There were no participants from USA (only two from Americas region) because National Voluntary Laboratory Accreditation Program (NVLAP) has already provided an accreditation programme[4] for SSL testing since 2009, for which NIST provides PT, and also NIST provides PT service for SSL testing under NIST Measurement Assurance Program (MAP) for accreditation bodies other than NVLAP. Since these PTs were conducted by NIST using a test method (IES LM-79 [6]), which is encompassed in the IC Test Method [5], and using basically the same types of comparison artefacts as those used in the IC 2013, it was agreed by the SSL Annex and NVLAP to link the test results. NIST contacted the laboratories who participated in the NVLAP PT or NIST MAP, and 35 US participants who gave permission to link their test results with IC 2013. This enabled the SSL Annex to include many USA laboratories in the comparison, as well as providing some possibility for these US laboratories to be recognised as PT in other countries. The z' scores of these linked laboratories were re-calculated according to the IC Generic Protocol [4]. The uncertainties of measurement were not reported in these PTs in NVLAP/NIST MAP and thus E_n numbers were not available in these linked data. The deviations from the IC Generic Protocol [4] and the IC Test Method [5] in these linked PTs were noted in the *Participants Results Report* issued to each linked laboratories, to be reviewed by ABs when it is used for an accreditation application.

After the IC was launched, Asia Pacific Laboratory Accreditation Cooperation (APLAC) launched a similar PT program (APLAC Proficiency Test T088) conducted in 2013. This programme was operated by NLTC using the same test method (i.e., the Interlaboratory Comparison Test Method 1.0 [5]) and the same artefact types used in IC 2013. For all of these reasons, it was agreed that the results of this APLAC PT programme could be linked to IC 2013, and laboratories registering for T088 were given the option of having their results linked to IC 2013. Twenty-one laboratories chose to be linked to IC 2013, which affords them the same benefits as participants in IC 2013 and allows more data to be included in the comparison. The APLAC PT used only E_n number, but z' scores according to the SSL Annex IC Generic Protocol [4] were also calculated for the laboratories with linked test results. Any other differences of the protocols used in the APLAC PT programme from the SSL Annex IC Generic Protocol [4] were noted in Participants Results Report (to be reviewed by ABs when it is used for accreditation application).

Thus, in total, the measurement data from 110 laboratories worldwide are included in this final report of IC 2013. In addition, there are 13 more sets of data included, as some laboratories submitted two or more sets of results for different measurement systems they used (e.g., integrating sphere and goniophotometer) or as a result of corrective action in the NVLAP PTs.

For comparison artefacts, at least four different LED lamps (directional, omnidirectional, low power factor, and high correlated colour temperature) and incandescent lamps (for reference purposes) were used, with one or two optional artefacts in some regions. Participants performed measurements of:

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[3] Draft of CIE TC2-71 at the time IC 2013 Test Method 1.0 was developed.

[4] NVLAP Energy Efficient Lighting Products, http://ts.nist.gov/standards/scopes/eelit.htm

- total luminous flux,
- active power,
- RMS voltage and current,
- luminous efficacy,
- chromaticity x and y,
- correlated colour temperature,
- colour rendering index (CRI Ra), and
- power factor (optional).

The differences of these measured results from the results by reference laboratory (Nucleus laboratories) were analysed, and z’ scores and E_n numbers (see sections 7.1 and 7.2) of these results were calculated. The denominators in z’ scores had been pre-determined in SSL Annex IC Generic Protocol when IC 2013 was launched.

Before this final report was prepared, *Participant Results Reports* (PRRs), providing individual test results of each laboratory were issued. PRRs are confidential documents, and each participant received a report containing just their individual results. If that laboratory then decides to apply for SSL testing accreditation, they may choose to submit their PRR as evidence of their proficiency, if their AB recognises IC 2013.

After completing the PRRs, the SSL Annex prepared four *regional Interim Reports*, which presented the results of all the participating laboratories in each region. The four Interim Reports were each prepared by the Nucleus laboratories and distributed to all the participants in each region. In the Interim Reports, the participants in the data are expressed anonymously but each participant was informed (confidentially) of their unique identification number so they can assess their results relative to the other laboratories. The regional Interim Reports are also made available to ABs and government agencies if requested. The requirements of ISO/IEC 17043 in reporting the results as a PT were satisfied by the PRRs and Interim Reports.

To date, IC 2013 has been recognised as a PT by National Voluntary Laboratory Accreditation Program (NVLAP) in USA, International Accreditation Japan (IA-Japan), China National Accreditation Service of Conformity Assessment (CNAS, China), Korea Laboratory Accreditation Scheme (KOLAS), and International Accreditation New Zealand (IANZ), and is expected to be recognised by more ABs.

Another purpose of IC 2013 was to provide the information on the current state of interlaboratory differences in SSL measurements worldwide, to identify problems and possibly improve measurement practices. This final report focuses on this aspect, presenting results of a technical and scientific interest, with limited information on test results as a PT. Also, the final report does not compare the laboratory performance in the different regions; the results of all regions are combined and presented together anonymously. Also, due to the large volume of data involving many participants, artefacts, and measurands, the data presented for z’ scores and E_n numbers are limited to certain representative data selected from all the artefacts and quantities tested. Some technical issues have been identified as a result of this IC, and thus, these results may be useful for future improvements to the measurement of LED lighting products.

2 Protocol of Comparison

The details of IC 2013 are described in the SSL Annex IC Generic Protocol [4]. IC 2013 was conducted by four Nucleus laboratories which served as reference laboratories in each region, as listed in Table 2-1. All the results of the four regions were combined for the results presented in this Final Report. The test method used was the SSL Annex IC Test Method 1.0 [5]. The five common artefact types and some additional (optional) artefacts that were used in this IC were specified in Generic Protocol, and the details are described in Section 5 of this final report. IC 2013 is the star type comparison (see Annex A of ISO/IEC 17043 for the types of PT schemes). The artefacts were measured by the reference laboratory first, sent to a participant laboratory for testing, and then returned and tested again by the reference laboratory (note: a small modification to this procedure was allowed in the Regional Protocol for AIST, NMIJ in Japan). If the observed drift (difference between the first and second measurements by reference laboratory) exceeded 0.8 x SDPA (see Section 7), then the relevant results of the artefact were discarded and a replacement artefact was sent for re-measurement. Each Nucleus laboratory developed its Regional Protocol in compliance with the SSL Annex IC Generic Protocol, with slight (regional) variations in the artefact types selected (see Section 5).

Table 2-1. List of Reference Laboratories

Nucleus Laboratory	Testing Coordinator	Testing Director
Dutch Metrology Institute (VSL, The Netherlands)	Elena REVTOVA	Nellie SCHIPPER
National Metrology Institute of Japan - Advanced Industrial Science and Technology (AIST, NMIJ, Japan)	Tatsuya ZAMA	Mamoru KAWAHARASAKI
National Lighting Test Centre (NLTC, China)	Wei ZHANG, Shuming HUA	Hongzheng XIN
National Institute of Standards and Technology (NIST, USA)	Cameron MILLER	Yoshi OHNO

3 Timetable

The IC 2013 was carried out on the time table given in Table 3-1. The dates for measurements listed are valid for the labs that directly participated in IC 2013. The dates of measurements linked from NIST MAP and NVLAP PT are from May 2010 to August 2013.

Table 3-1. Timetable of SSL Annex IC 2013

Item	Date
Announcement and opening of application period	22 October 2012
Closure of the application period	30 April 2013
Measurements conducted with the Participants	November 2012 – August 2013
Participants Results Reports and Regional Interim Reports issued	January 2014
International Final Technical Report	June 2014

4 List of Participants

The list of participants for each Nucleus laboratory are shown in Tables 4-1 to 4-4. These are not all of the participants, only laboratories who gave consent are listed. There were 26 labs under VSL, 14 labs under NLTC, 12 labs under AIST, NMIJ, and 37 labs under NIST including 35 labs linked from NVLAP/NIST MAP programmes. In addition to these, there were also 21 labs linked from APLAC PT but these labs are not listed below.

The number of laboratories who participated directly in IC 2013 in the Americas region was small because the need for a SSL PT in North America has largely been met, as NIST had already provided PT services for the NVLAP EEL-SSL program and NIST Measurement Assurance Program (MAP) for many labs in USA and Canada when IC 2013 was launched.

Table 4-1. List of Participants under AIST, NMIJ, approved to be listed

Laboratory/Institute	Country
Japan Electrical Safety & Environment Technology Laboratories	Japan
Hitachi Appliances, Inc.	Japan
Toshiba Lighting & Technology Corporation	Japan
NEC Lighting, Ltd.	Japan
Otsuka Electronics Co., Ltd.	Japan
Panasonic Corporation Eco Solutions Company	Japan
Tokyo Metropolitan Industrial Technology Research Institute	Japan

Table 4-2. List of Participants under VSL, approved to be listed

Laboratory/Institute	Country
Centre Scientifique et Technique du Bâtiment - CSTB Grenoble	France
DELTA	Denmark
DTU Fotonik	Denmark
Instrument Systems GmbH	Germany
Intertek Semko AB	Sweden
Laboratorium voor Lichttechnologie / KAHO Sint-Lieven	Belgium
Korea Institute of Lighting Technology (KILT)	Republic of Korea
Korea Photonics Technology Institute (KOPTI)	Republic of Korea
Korea Testing Certification (KTC)	Republic of Korea
Korea Testing Laboratory (KTL)	Republic of Korea
Korea Testing & Research Institute (KTR)	Republic of Korea
LED Engineering Developments	France
Laboratoire Plasma et Conversion Energie (LAPLACE)/Université P. Sabatier	France
National Physical Laboratory	United Kingdom
Nederlandse Voedsel- en Warenautoriteit (NVWA)/Laboratory Non-Food Product Safety	The Netherlands
NEOLUX	France
OSRAM GmbH Central Laboratory for Light Measurements	Germany
Philips Innovation Services	The Netherlands
PISEO SAS	France
Russian Lighting Research Institute named by S.I.Vavilov (VNISI)	Russia
SP Technical Research Institute of Sweden	Sweden
SSL Resource	Finland
The Lighting Industry Association Laboratories Ltd	United Kingdom

Table 4-3. List of Participants under NIST, approved to be listed (including two direct participants to IC 2013 and 35 laboratories linked from NVLAP PT or NIST MAP)

Laboratory/Institute	Country
Acuity Brands Lighting Granville Lab	USA
Acuity Brands Lighting, Conyers	USA
Aurora International Testing Laboratory	USA
Bay Area Compliance Laboratory Corporation	USA
Cooper Lighting	USA
Cree Durham Technology Center (DTC)	USA
CREE Engineering Services Testing Laboratory	USA
CREE, Inc.	USA
CSA Group	USA
EYE Lighting International of North American, Incorporated	USA
Gamma Scientific Incorporated	USA
GE Lighting Nela Park	USA

Laboratory/Institute	Country
Halco Lighting Laboratory	USA
Hubbell Lighting, Inc.	USA
Independent Testing Laboratories, Incorporated	USA
INMETRO	Brazil
Intertek Commercial & Electrical	USA
University of California, Davis	USA
Intertek Testing Services	USA
Juno Lighting Group	USA
Kenall Performance Laboratory	USA
Light Laboratory, Incorporated	USA
Lighting Research Center	USA
Lighting Sciences Incorporated	USA
LightLab International, Incorporated	USA
Lumentra Inc.	USA
National Research Council of Canada	Canada
Orb Optronix, Incorporated	USA
Osram Sylvania Metrology & Analytics Services	USA
Philips Day-Brite Lighting	USA
Philips Lighting Company	USA
Sapphire Technical Solutions, LLC	USA
Sternberg Lighting	USA
TUV SUD America	USA
UL Verification Services, Inc.	USA
UL / Luminaire Testing Laboratory, Inc.	USA

Table 4-4. List of Participants under NLTC, approved to be listed

Laboratory/Institute	Country
Foshan Electrical and Lighting Co., Ltd.	China
ITRI Optoelectronic Semiconductor Measurement Laboratory	Taiwan
Light Engine Limited	China
Lighting Test and Evaluation Laboratory, Residential & Commercial Energy Conservation Technology Division, Energy and Environment Research Laboratories. ITRI	Taiwan
Massey University	New Zealand
National Measurement Institute Australia	Australia
Queensland University of Technology	Australia
Shanghai Qiangling Electronic co, Ltd.	China
Steve Jenkins and Associates Pty. Ltd.	Australia
Swedish Energy Agency	Sweden
Taiwan Electric Research & Testing Center (TERTEC)	Taiwan
Zhejiang Shenghui Lighting Co., Ltd.	China
Intertek Testing Services Hong Kong, Ltd.	Hong Kong
Optical and Electrical Testing Laboratory, CMS, ITRI	Taiwan

Each participant laboratory was given a “Lab Code” to identify them, but Lab Codes are not used in this final report due to the practical limitations on space in the figures. Therefore, Laboratory Numbers from 1 to 123 are used to present the results in this final report. Table 4-5 shows the correspondence between the Laboratory Numbers and the Lab Codes. Lab Codes that appear with a star are those of laboratories that are linked from the NVLAP/NIST PT or the APLAC PT. Each participant has been given their Lab Code, but that code is kept confidential. The Lab Codes were assigned to laboratories randomly so the participants in the four regions are all mixed together in the graphs shown in section 9.

Table 4-5. Correspondence between Laboratory Numbers and Lab Codes

Lab Num.	Lab Code	Lab Num.	Lab Code	Lab Num.	Lab Code	Lab Num.	Lab Code	Lab Num.	Lab Code	Lab Num.	Lab Code
1	P011*	22	L168	43	L268-f*	64	L386-f*	85	L552*	106	L712
2	L045	23	L171	44	L273-S*	65	L395	86	L553*	107	L717
3	L059-S*	24	L176	45	L273-G*	66	L405	87	L567*	108	P725*
4	L059-G*	25	P185*	46	L275*	67	P416*	88	L568	109	L733
5	L061	26	P189*	47	L282	68	P424*	89	L571*	110	L734
6	L066	27	L199	48	P294*	69	L424	90	L579	111	L737
7	L082-S*	28	L208	49	L303-S*	70	L430	91	L582*	112	L758
8	L082-G*	29	L213	50	L303-G*	71	L436-S*	92	L584*	113	L764-S*
9	L082-G2*	30	L227	51	L304	72	L436-G*	93	L594	114	L764-G*
10	L087	31	L228*	52	L306	73	L438	94	P600*	115	L764-G2*
11	P097*	32	L235	53	L332*	74	L449*	95	L603	116	L774
12	L112	33	L236*	54	P342*	75	L459*	96	L607*	117	P774*
13	L130	34	L239-i*	55	L354	76	L462	97	L616*	118	L777
14	P142*	35	L239-f*	56	L359	77	L479	98	P630*	119	L797
15	L144	36	L241	57	L362	78	L488	99	L633	120	L799
16	L149-S*	37	L245*	58	L369-S*	79	L511*	100	L638*	121	P850*
17	L149-G*	38	L247*	59	L369-G*	80	L518*	101	P639*	122	P895*
18	P149*	39	L248	60	L376*	81	L521*	102	L646	123	P920*
19	P153*	40	L256	61	L379	82	L536*	103	L687*		
20	L155	41	L265*	62	L385	83	L547	104	P693*		
21	P158*	42	L268-i*	63	L386-i*	84	L551	105	L708		

Some laboratories submitted two or three sets of results using different measurement systems. In this case, a separate Lab Code (ending with -S for sphere system and -G for goniophotometer) was issued for each measurement system and those results are treated as a different laboratory. Also, for some of the laboratories linked from NVLAP/NIST PT, results before and after a corrective action are included as separate laboratories, and are given Lab Codes ending with -i (initial test) or -f (final test).

5 Description of the Artefacts

The SSL Annex IC Generic Protocol [4] specified five different types of artefact to be used in this IC:

1) Incandescent lamp (I-AC)
2) Omnidirectional LED lamp (OD)
3) Directional LED lamp (D)
4) High CCT LED lamp or luminaire (HCCT) (> 5000 K, preferably ≈ 6500 K)
5) Low power-factor LED lamp (LPF) (PF < 0.6, preferably PF ≈ 0.5)

In addition, each region was given the option to add artefacts, including the following:

1) Incandescent lamp – DC operation (I-DC), using the same lamp as I-AC
2) Tubular type LED lamp (TL)
3) Remote-phosphor type LED lamp (RP)

The abbreviations in parenthesis (e.g., I-AC, OD, etc.) for these artefact types are used in this document. The Generic Protocol allowed the Nucleus Labs to combine one of these optional artefacts with one of the four basic LED lamp types. These different products were included in IC 2013 to compare and identify differences in the results due to different artefact characteristics (e.g., differences in spectral distribution, differences in angular intensity distribution, differences in current waveform, etc.) or to possibly identify additional measurement problems with specific lamp types such as tubular and remote-phosphor lamps.

The artefacts used were selected by each Nucleus laboratory for the region according to the SSL Annex IC Generic Protocol [4] and also considering the needs in the region. The types of product used in each region are listed in the corresponding Regional Protocols, and are presented below in Tables 5-1 to 5-4. The artefacts were aged, tested and screened for stability by the Nucleus Laboratory prior to being used for comparison testing. NIST-D1 (directional LED luminaire) is not listed in the Generic Protocol but was added because this type of product is quite common in USA and it was used in the PTs in NVLAP/NIST MAP. Note that there were some variations in rated power and nominal CCT in the artefacts used in the PTs in NVLAP/NIST MAP.

Several sets of artefacts were prepared by each Nucleus laboratory and used in this comparison. Each LED lamp or luminaire sent to participants was given a unique artefact identification number. The artefacts used in each of the four regions (as described in Regional Protocols) are shown below.

Table 5-1. AIST, NMIJ Artefacts and their Properties

Identifier	Type	Rated Voltage	Rated Power	Nominal CCT	Other Conditions
AIST-IDC	Incandescent DC	100 V DC	200 W	2800 K	Using the same lamp as AIST-IAC
AIST-IAC	Incandescent AC	100 V AC	200 W	2800 K	AC frequency: 50 Hz Operating position: base up for all lamps.
AIST-OD	Omni-directional	100 V AC	9.0 W	3000 K	
AIST-D	Directional	100 V AC	5.0 W	3000 K	
AIST-HCCT	High CCT	100 V AC	9.0 W	5100 K	
AIST-LPF	Low power factor	100 V AC	11.4 W	6000 K	

Table 5-2. VSL Artefacts and their Properties

Identifier	Type	Rated Voltage	Rated Power	Nominal CCT	Other Conditions
VSL-IAC	Incandescent AC	230 V AC	100 W	3000 K	AC frequency: 50 Hz Operating position: base up for all lamps except VSL-TL, which is horizontal.
VSL-RP	Omni-directional (and Remote Phosphor)	230 V AC	12 W	2700 K	
VSL-D	Directional (and high CCT)	230 V AC	5 W	5000 K	
VSL-LPF	Low power factor	230 V AC	5 W	3200 K	
VSL-TL*	High CCT (and Tubular)	230 V AC	18 W	6000 K	

* The TL lamp is 1.2 m in length.

Table 5-3. NIST and NVLAP PT/NIST MAP Artefacts and their Properties

Identifier	Type	Rated Voltage	Rated Power	Nominal CCT	Other Conditions
NIST-IAC	Incandescent AC	120 V AC	60 W	2900 K	AC frequency: 60 Hz Operating position: base up for all lamps.
NIST-OD	Omni-directional	120 V AC	12.5 W	2700 K	
NIST-D1	Directional (downlight)	120 V AC	12.0 W	2700 K	
NIST-D2	Directional (lamp)	120 V AC	8.0 W	3000 K	
NIST-LPF	Low power factor	120 V AC	6.0 W	4500 K	
NIST-HCCT*	High CCT	12 V DC	2.9 W	6500 K	Constant current 0.2250 A

* NIST-HCCT is an under-cabinet LED luminaire with 60 cm in length, operated on the specified DC current.

Note: there were some variations of rated power and CCT of lamps used in NVLAP/NIST PT.

Table 5-4. NLTC and APLAC PT Artefacts and their Properties

Identifier	Type	Rated Voltage	Rated Power	Nominal CCT	Other Conditions
NLTC-IAC	Incandescent AC	220 V AC	60 W	2700 K	AC frequency: 50 Hz Operating position: base up for all lamps
NLTC-OD	Omni-directional	220 V AC	5 W	2700 K	
NLTC-D	Directional	220 V AC	8 W	3000 K	
NLTC-HCCT	High CCT	220 V AC	6 W	5000 K	
NLTC-LPF	Low power factor	220 V AC	6 W	3000 K	
NLTC-IDC*	Incandescent DC	12 V DC	50 W	2800 K	Constant current: DC 3.9500 A.

* NLTC-IDC is a tungsten halogen lamp, and was used only at APLAC PT (instead of NLTC-IAC).

6 Measurands

The following measurement quantities were measured and compared in this IC test.

1) Total luminous flux (lm)
2) RMS Voltage (V) and Current (A)
3) Electrical active power (W)
4) Luminous efficacy (lm/W)
5) Chromaticity coordinates *x, y*
6) Correlated Colour Temperature (K)
7) Colour Rendering Index (CRI) R_a
8) Power factor (optional)

Reporting measurement uncertainties in compliance with ISO/IEC Guide 98-3 [7] was required by the SSL Annex Test Method 1.0 [5] for all results. However, results without uncertainty values were also accepted (noted as a non-compliance to the IC test method), as such results may still qualify for certain testing accreditation programmes that do not require uncertainty values in test reports.

7 Assigned Values and Data Analysis

The assigned value is a value attributed to a particular property of a proficiency test item [1]. Assigned values in IC 2013 were given by the Nucleus Laboratories, and were calculated as the mean of the measurements by the Nucleus Laboratory taken for each quantity before sending and after return of artefacts from each participating laboratory. The criteria used to analyse and evaluate the performance are given by the *z'* score (defined in ISO 13528 [8]) and E_n number (defined in ISO 13528 [8] and ISO/IEC 17043 [1]). However, it should be noted that the E_n numbers were not calculated if the uncertainties were not reported by a participant.

7.1 z' score

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

$$z' = \frac{x - X}{\sqrt{\hat{\sigma}^2 + u_X^2 + u_{\text{drift}}^2}}, \qquad (1)$$

where $\hat{\sigma}$ is the SDPA value (Standard Deviation for Proficiency Assessment) and, in this IC test, is the generic standard uncertainty of a participant's measurement; u_x is the standard uncertainty of the reference value (average of uncertainties of measurement of the comparison artefacts by four Nucleus laboratories reported in the Nucleus Laboratory Comparison Report published in 2012 [3]). The value of u_{drift} is the uncertainty contribution from the expected artefact drifts (controlled to within 0.8 x SDPA, see Section 2) and calculated by:

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

If these equations are given in relative uncertainties $\hat{\sigma}_{\mathrm{rel}}$, $u_{X,\,\mathrm{rel}}$, $u_{\mathrm{drift,\,rel}}$, then *z'* is calculated by:

$$z' = \frac{(x - X)/X}{\sqrt{\hat{\sigma}_{\mathrm{rel}}^2 + u_{X,\mathrm{rel}}^2 + u_{\mathrm{drift,\,rel}}^2}}, \tag{3}$$

where *x* is the value measured by the participant and *X* is the assigned value measured by the reference laboratory. The values of u_X or $u_{X,\,\mathrm{rel}}$ and $\hat{\sigma}$ or $\hat{\sigma}_{rel}$ were pre-determined, and are listed in Table 2 in the SSL Annex IC Generic Protocol [4]. The values of u_X or $u_{X,\,\mathrm{rel}}$ were determined as the averages of the Nucleus Laboratories' measurement uncertainties reported in the preceding comparison among the Nucleus Laboratories [3]. The values of $\hat{\sigma}$ or $\hat{\sigma}_{rel}$ were determined as expected generic uncertainties of measurement of each quantity by the participants.

The determined values of these parameters used in IC 2013 and their uncertainty budget are provided in in Appendix 1 of this Report; and also in the Regional Interim Reports previously distributed in each region.

7.2 E_n number

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

$$E_{\mathrm{n}} = \frac{x - X}{\sqrt{U_{\mathrm{lab}}^2 + U_{\mathrm{ref}}^2}}, \tag{4}$$

where:

x: value measured by the participant

X: assigned value (average of reference 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

$$u_{\mathrm{ref}} = \sqrt{\left(\frac{u_1 + u_2}{2}\right)^2 + \left(\frac{X_1 - X_2}{2\sqrt{3}}\right)^2} \tag{5}$$

and

$$U_{\mathrm{ref}} = 2\ u_{\mathrm{ref}}, \tag{6}$$

where X_1 and X_2 are measured values by the reference laboratory, before and after the participant's measurement, and u_1 and u_2 are their absolute standard uncertainties at the first and second measurements. Equation (5) above assumes that the two measurements by the reference laboratory are fully correlated. The second term in the square root is a square of the standard uncertainty associated with the drift of the artefacts as measured by the reference laboratory (taken as a rectangular distribution [7],[9]).

7.3 Use of z' and E_n

Generally, $|E_{\mathrm{n}}|$ > 1.0 is considered to be unsatisfactory. That is, the difference in the quantities measured by the Nucleus and participant laboratories is greater than the expanded uncertainty of the comparison. The value of $2.0 < |z'| < 3.0$ is considered to be questionable, and $|z'| \geq 3.0$ is generally considered to be unsatisfactory, but the judgment as to whether the result is acceptable will depend on the AB.

The E_n number and z' score are used for different purposes. The concept of the E_n number is to test whether the claimed measurement uncertainties of a laboratory are valid, and this is suitable when the uncertainty is in the scope of accreditation and needs to be certified (typically the case for *calibration laboratory accreditation*). The z' score, on the other hand, is to test whether the laboratory's results are within an acceptable range of variation, and is suitable for *testing laboratory accreditation* (supporting product certification activities) which examines the laboratory's competence and compliance to the reference test method. For laboratory accreditation programmes having both purposes (i.e., serving for product certification activities as well as certifying the reported uncertainties), the use of both the E_n number and z' score would be appropriate.

8 Results of Reference Laboratory Measurements

In this report, the participants' results are presented in (relative) differences to the value measured by reference laboratory (presented in section 9), and the measured values of reference laboratories and of participants are not presented. To provide information of the magnitude of the absolute values of the measurement quantities of each artefact, the measurement results for one set of the artefacts measured by NIST are presented as an example in Table 8-1 and their uncertainties in Table 8-2. NIST used several artefact sets. The values for other artefact sets were similar to these.

Table 8-1. Measurement results of one of the artefact sets measured by NIST

Artefact Tested	Voltage	Current	Active Power	Luminous Flux	Luminous Efficacy	x	y	CCT	CRI Ra	Power Factor
Unit:	(V)	(A)	(W)	(lm)	(lm/W)			(K)		
NIST-IAC	120.00	0.506	60.76	999.4	16.45	0.4482	0.4086	2855	99.6	1.000
NIST-OD	120.02	0.141	12.80	853.9	66.69	0.4580	0.4073	2701	81.3	0.755
NIST-D1	119.98	0.089	10.21	671.8	65.81	0.4613	0.4031	2622	92.3	0.960
NIST-D2	120.19	0.077	8.80	318.6	36.22	0.4295	0.3970	3070	89.0	0.951
NIST-LPF	119.94	0.066	4.61	210.4	45.79	0.3591	0.3856	4663	66.6	0.582
NIST-HCCT	11.98	0.225	2.70	115.1	42.68	0.2958	0.3116	7796	81.7	1.000

Table 8-2. (Relative) expanded uncertainties (k=2) of measurements by NIST

Artefact Tested	Voltage	Current	Active Power	Luminous Flux	Luminous Efficacy	x	y	CCT	CRI Ra	Power Factor
***Unit*:**	%	%	%	%	%			(K)		
NIST-IAC	0.3	0.2	0.5	0.5	0.7	0.002	0.002	20	0.5	0.002
NIST-OD	0.3	1.2	1.3	0.7	1.5	0.002	0.002	20	0.5	0.010
NIST-D1	0.3	0.8	0.9	0.7	1.1	0.002	0.002	20	0.5	0.008
NIST-D2	0.3	0.7	0.8	0.7	1.1	0.002	0.002	20	0.5	0.005
NIST-LPF	0.3	0.4	0.8	0.7	1.1	0.002	0.002	20	0.5	0.006
NIST-HCCT	0.2	0.4	0.6	0.7	0.9	0.002	0.002	50	0.5	0.018

Each artefact was measured by the Nucleus laboratory before and after transportation to each participating laboratory. The observed Before-After differences indicate changes in the artefact performance, possibly due to instability of artefact, effects of transportation, and/or measurement reproducibility at the Nucleus laboratory. Figures 8-1 to 8-4 show examples of the (relative) differences between the first (before) and second (after) measurements of all quantities of 15 representative artefact sets used in this IC. In the graphs below, reference laboratories of the data are mixed and the dashed line shows 0.8 x $\hat{\sigma}$. If the change exceeded ±0.8 x $\hat{\sigma}$, the data of the artefact were discarded and additional measurements were made on a replacement artefact. These graphs show the initial data as measured in IC 2013, thus some data points exceed the limit.

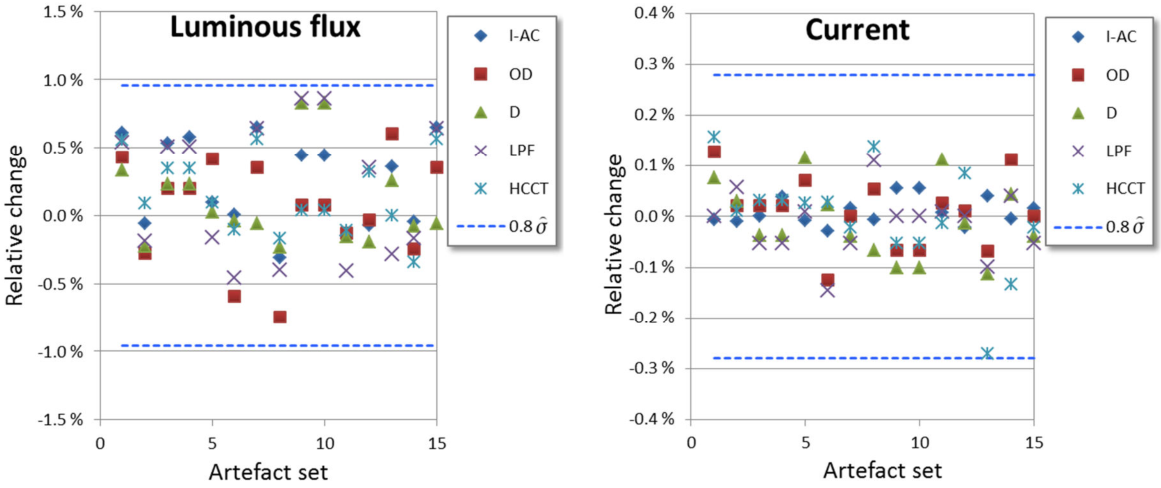

Figure 8-1. Examples of relative differences between two measurements by Reference Laboratories before and after transportation, for luminous flux and RMS current

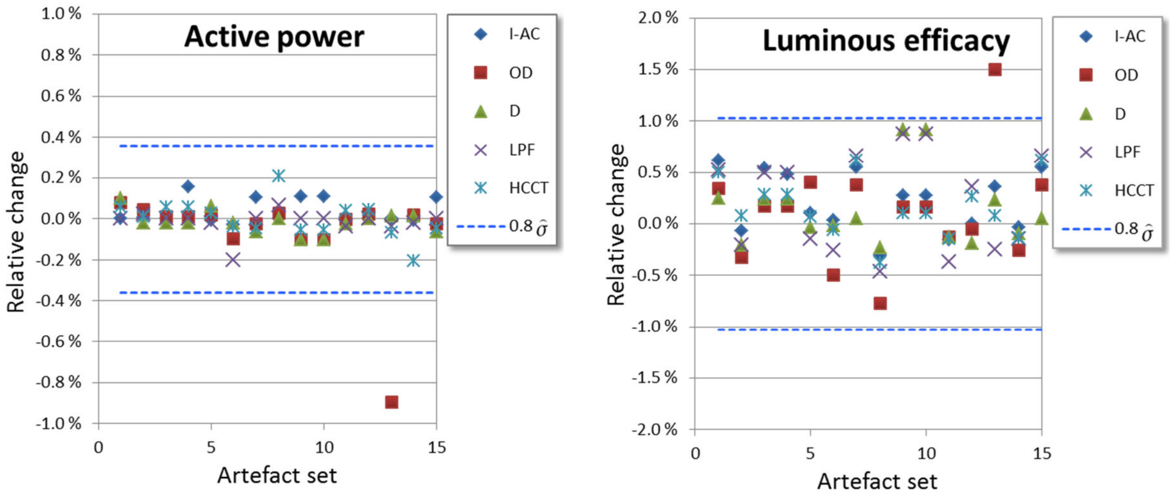

Figure 8-2. Examples of relative differences between two measurements by Reference Laboratories before and after transportation, for active power and luminous efficacy

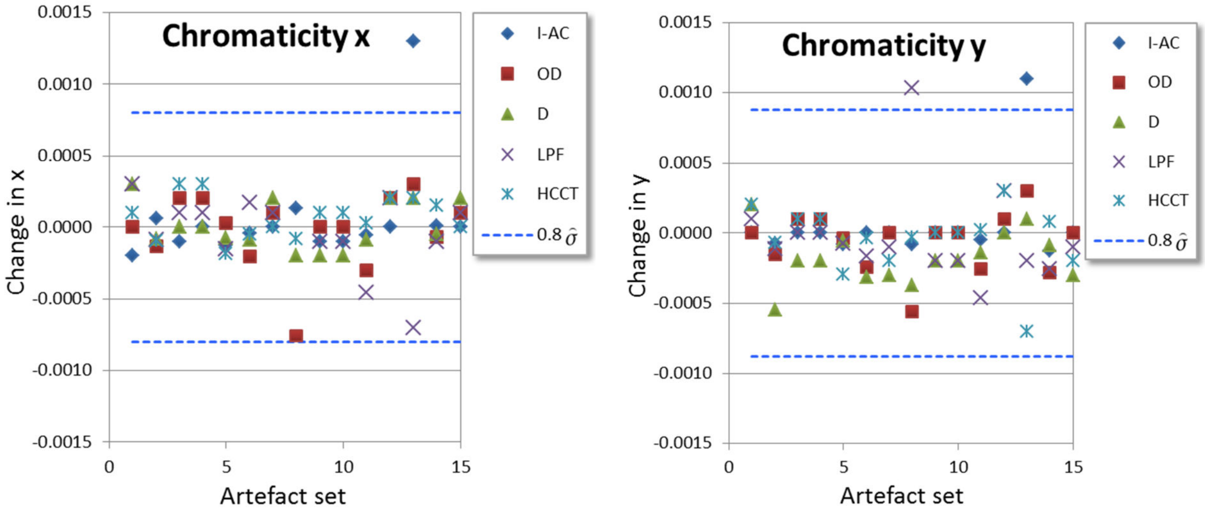

Figure 8-3. Examples of differences between two measurements by Reference Laboratories before and after transportation, for chromaticity x and y

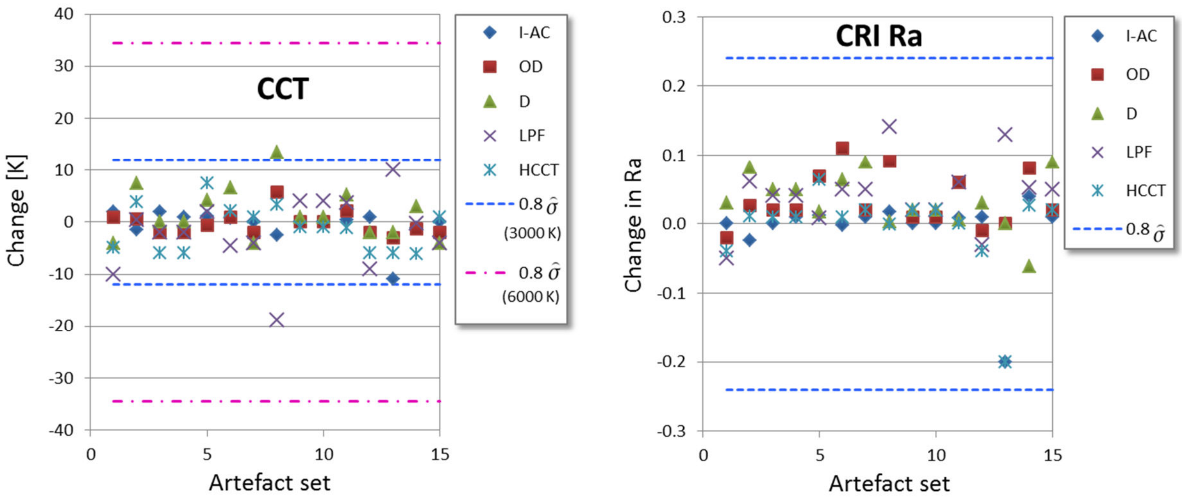

Figure 8-4. Examples of differences between two measurements by Reference Laboratories before and after transportation, for CCT and CRI R_a

9 Results of the Participants Measurements

The results of IC 2013 were first analysed in each region with the assigned values as the values measured by the regional reference laboratory (Nucleus Laboratory), then the results of all the regions were combined based on the equivalence among the Nucleus Laboratories [3]. The differences between the participants' measurement values and the assigned values, z' scores and E_n numbers, of all measured quantities of all the artefacts, for all participants, were determined. The numerical results of these values for all conditions were reported in the Participants Results Reports, and the graphical presentations of all these results in each region were reported in the Regional Interim Reports (issued by each Nucleus Laboratory) for accreditation purposes. This Final Report presents graphical results of the differences in all conditions, but the z' scores and E_n numbers are presented only for certain conditions for technical discussions.

Please note that results of RMS voltage are not included in these analyses, as this is a set parameter (in most cases) and it would not make sense to compare a set parameter. If the set parameter of an artefact is current (NLTC-IDC, NIST-HCCT), the results of current measurements of such artefacts are excluded from the analyses. Also, the results of DC-operated artefacts (AIST-IDC, NLTC-IDC, NIST-HCCT) are excluded from the power factor analyses.

In Section 9.1, the differences between the participant's measurement values and the assigned values are presented, with participants' reported uncertainties (if these are reported) shown for all participants. The results for all quantities and all types of artefact are reported. The relative differences in percentage are presented for all photometric and electrical quantities except for power factor (reported in absolute difference) and colorimetric quantities (presented in absolute units).

Section 9.2 presents the uncertainties of measurements of all quantities and all artefacts reported by the participants, and some analyses are provided.

In Sections 9.3 and 9.4, the z' scores and E_n numbers are presented for selected types of artefact (incandescent-AC and low power factor lamp). Each laboratory number (1 to 123) corresponds to each participant or, in some cases, each measurement system of a participant.

Note that not all data points are plotted for all laboratory numbers in each figure. For example, the APLAC PT used incandescent lamps with DC operation, so their data are not included in "I-AC" figures. Some laboratories did not measure colorimetric quantities and reported only photometric and electrical quantities. When a participant submitted two or more sets of results for different measurement systems (identified by separate laboratory numbers), only a partial set of quantities and artefacts were measured by the additional measurement system(s) (e.g., additional goniophotometer results often reported only photometric and electrical quantities, not colorimetric quantities.) Also, only a limited number of laboratories reported power factor, as it was an optional measurand.

All laboratories reported which measurement system (sphere or goniophotometer) they used. In some cases, a laboratory used both systems, e.g., photometric quantities by a goniophotometer and colorimetric quantities by a sphere system. Comparisons of results using different instruments are reported in Section 9.1.10.

The results of optional artefact types (remote phosphor, tubular type, and incandescent lamp by DC operation) are presented in Section 9.1.11.

9.1 Differences in measurement results

The (relative) differences of results between the participant (Lab) and the Nucleus laboratory (Ref), defined by (Lab - Ref) or (Lab - Ref)/Ref, for all quantities, all participants, and all artefact types are presented in graphic forms in the following subsections. The horizontal axis (from 1 to 123) indicates individual participant laboratories (laboratory numbers), where the order of laboratories from the four different regions has been mixed.

The error bars in the figures show the uncertainties of measurement (expanded uncertainty with a coverage factor, k=2) by the participants, and are shown only when the uncertainties were reported. Note that all NVLAP-linked results do not include uncertainties. There are a few cases where laboratories reported uncertainties but not for colour quantities. Note that when a data point does not have an error bar, it means, in most cases, no uncertainty was reported, but in some cases, the reported uncertainty value is so small that bar is hidden behind data point. To clarify this, see section 9.2 for separate presentations of reported uncertainties.

The dashed lines in the figures (in pink) show the average values of the uncertainties (k=2) by the reference (Nucleus) laboratories for all the points plotted in each figure. The reference laboratory uncertainty values are similar to but not necessarily the same as those reported in the Nucleus Laboratory Comparison Report [3] and in the IC Generic Protocol [4] due to slightly different products used in the IC 2013 in each region.

9.1.1 Total luminous flux

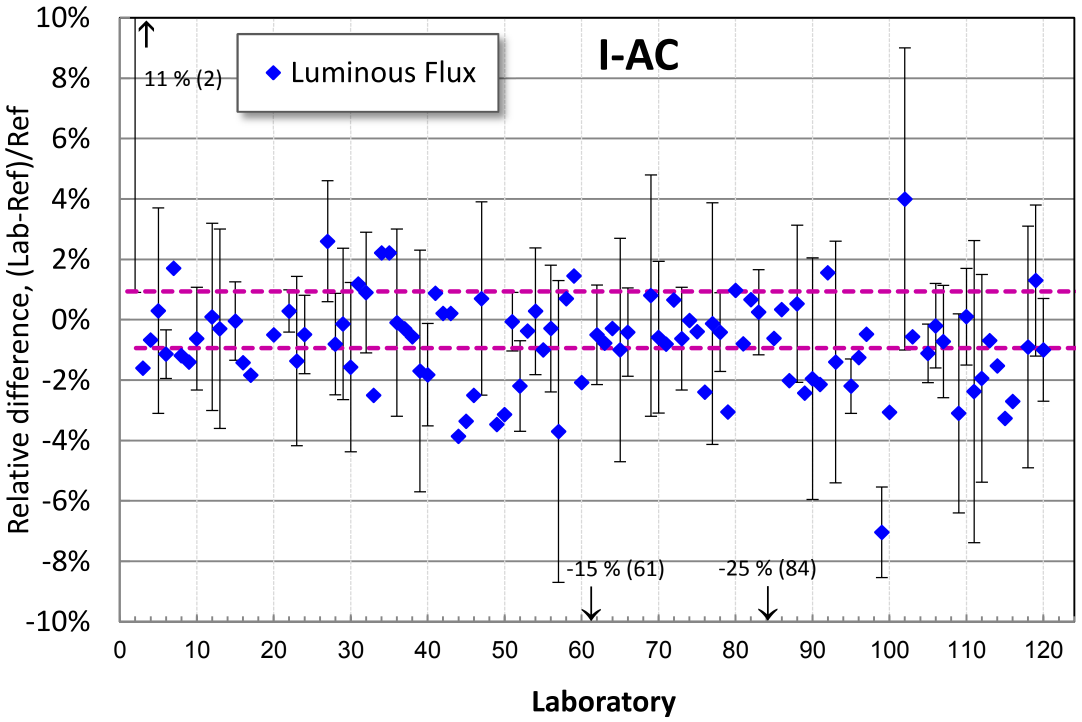

Figure 9-1. Relative differences of total luminous flux for Incandescent lamp AC operation (I-AC)

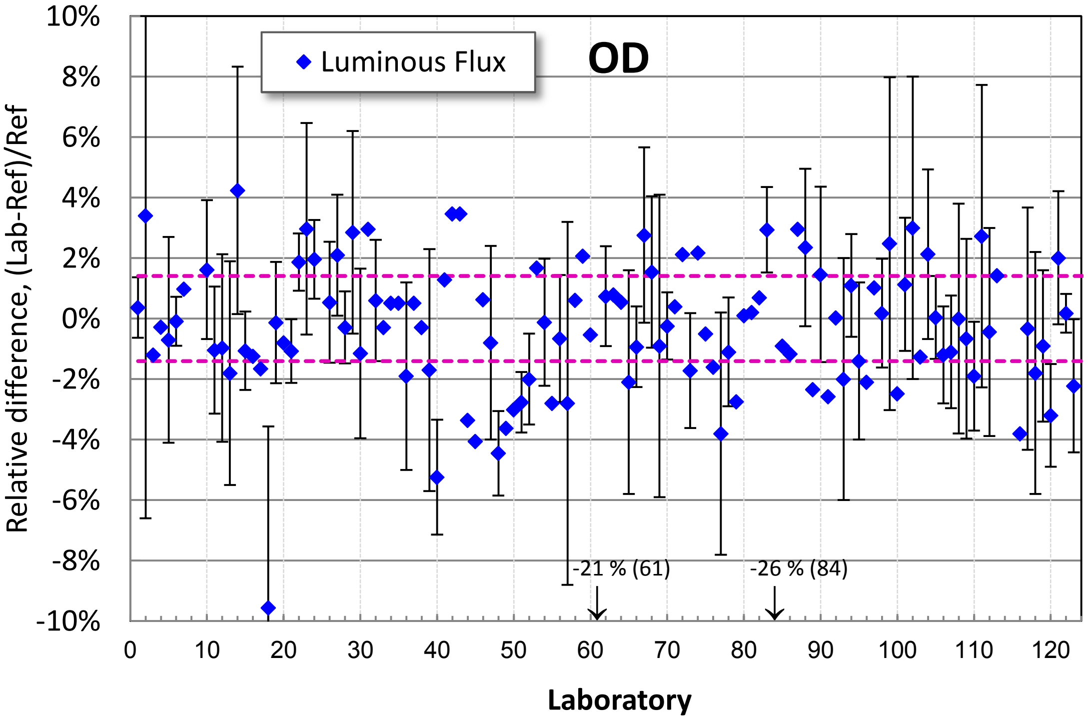

Figure 9-2. Relative differences of total luminous flux for omnidirectional LED lamp (OD)

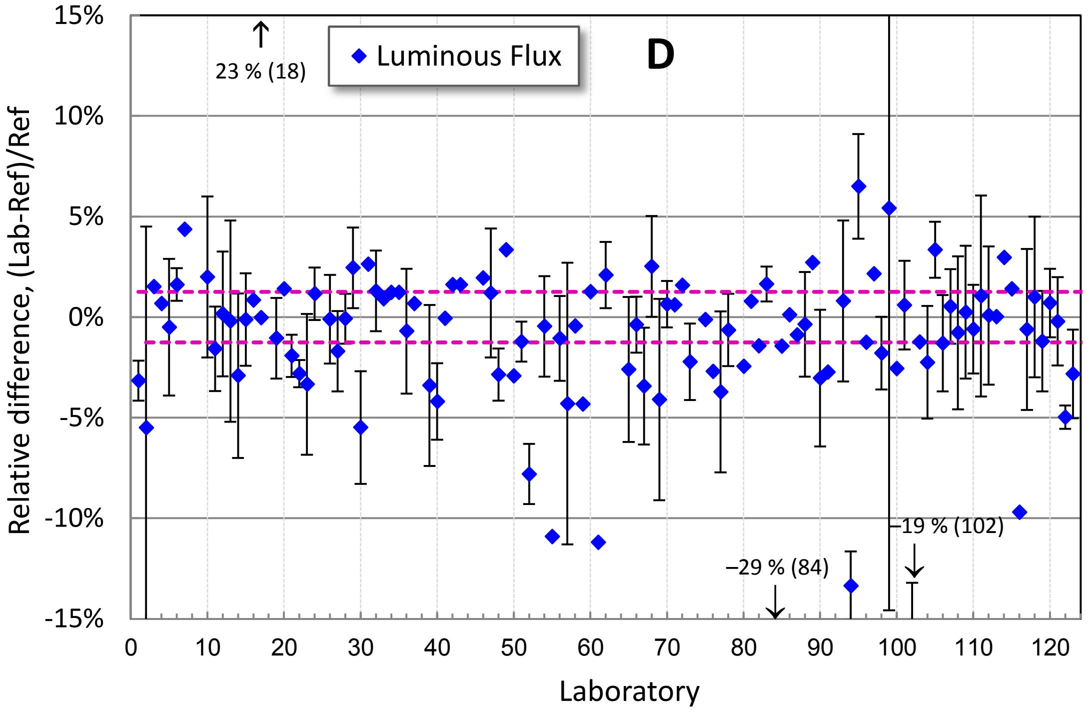

Figure 9-3. Relative differences of total luminous flux for directional LED lamp (D)

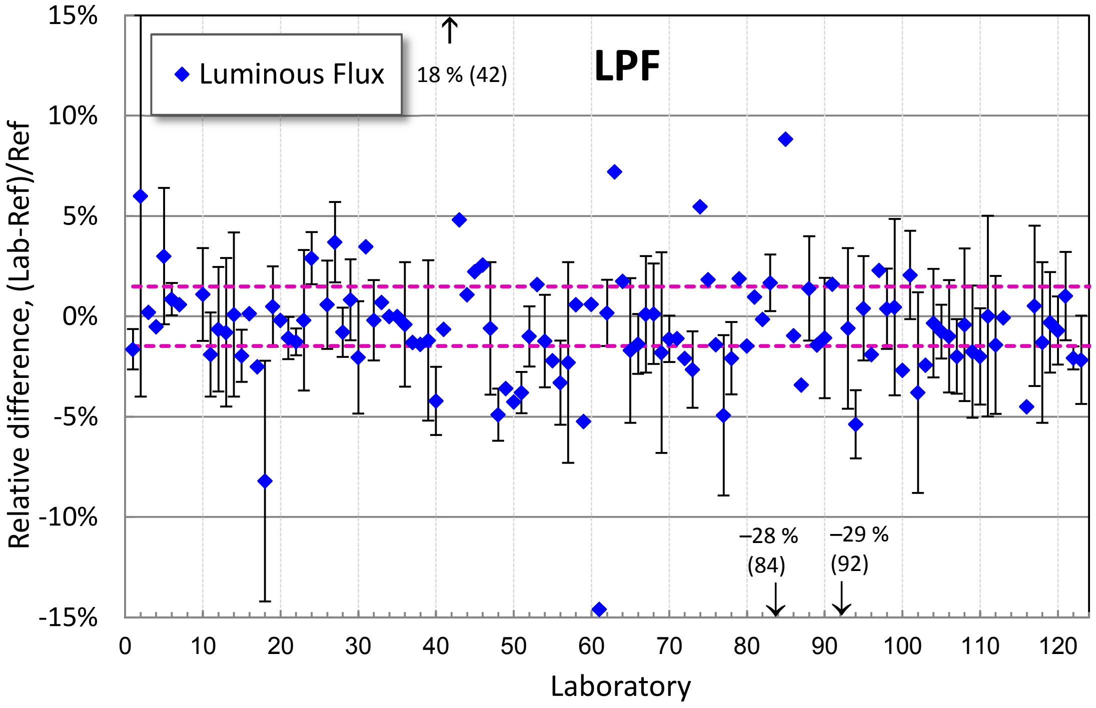

Figure 9-4. Relative differences of total luminous flux for low power factor lamp (LPF)

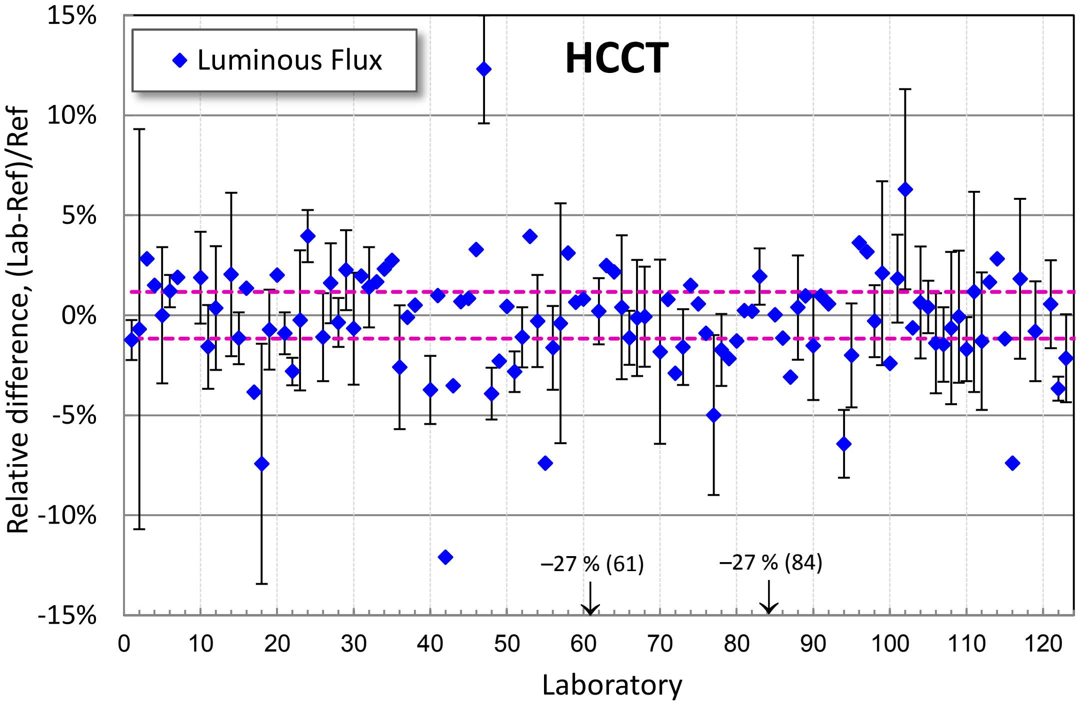

Figure 9-5. Relative differences of total luminous flux for high CCT lamp (HCCT)

To compare the variations of results across the artefact types, the measured differences in the data have been analysed using *robust standard deviation*. Robust standard deviation is described in Algorithm A, Annex C, ISO 13528:2005 [8], which provides a standard deviation calculation method that minimises the effects of extreme points (outliers). Figure 9-6 shows the comparison of the relative differences of total luminous flux using *robust standard deviation* for the five different artefact types. It shows that the variations in measurements of the LED lamps (on the average) are 1.6 times larger than the variations for an incandescent lamp, which demonstrates the significant additional uncertainty components for LED lamps. However, differences between the different types of LED lamps are not significant.

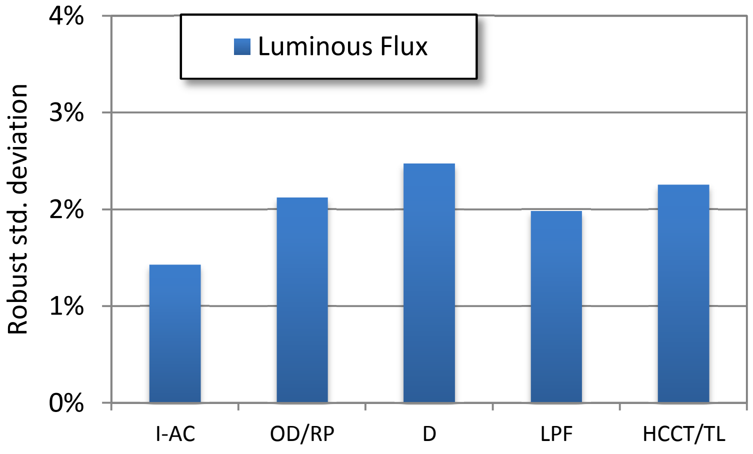

Figure 9-6. Summary of relative differences of total luminous flux. The bars show robust standard deviations of the relative differences of all laboratories for each type of lamp.

9.1.2 Luminous efficacy

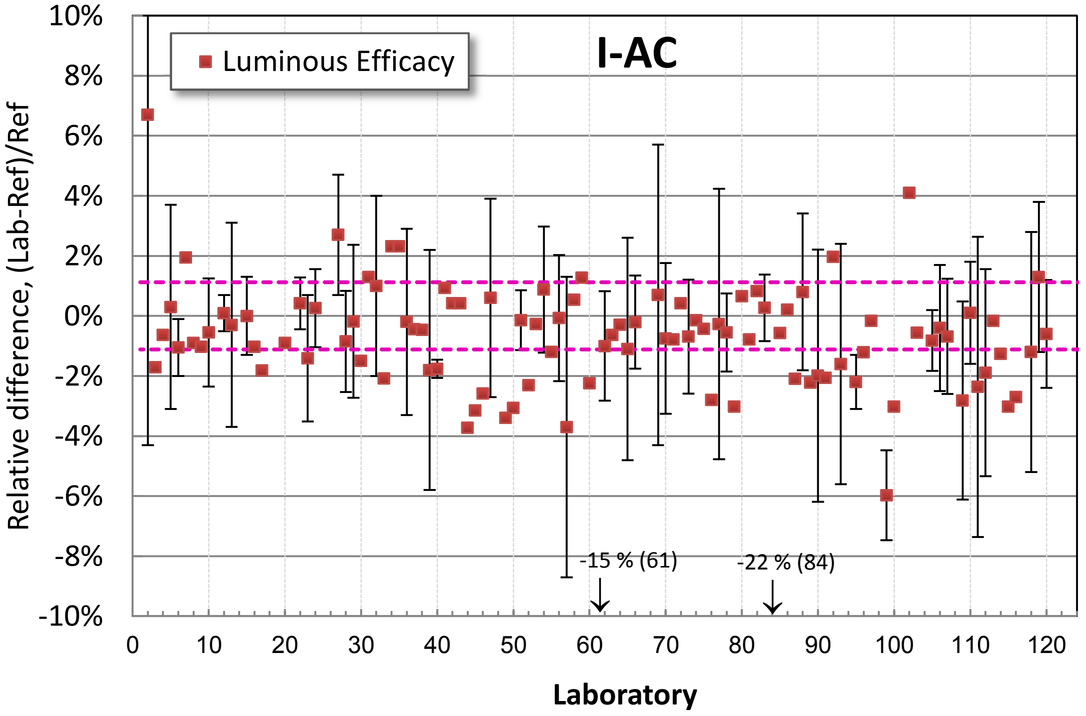

Figure 9-7. Relative differences of luminous efficacy for Incandescent lamp, AC operation (I-AC)

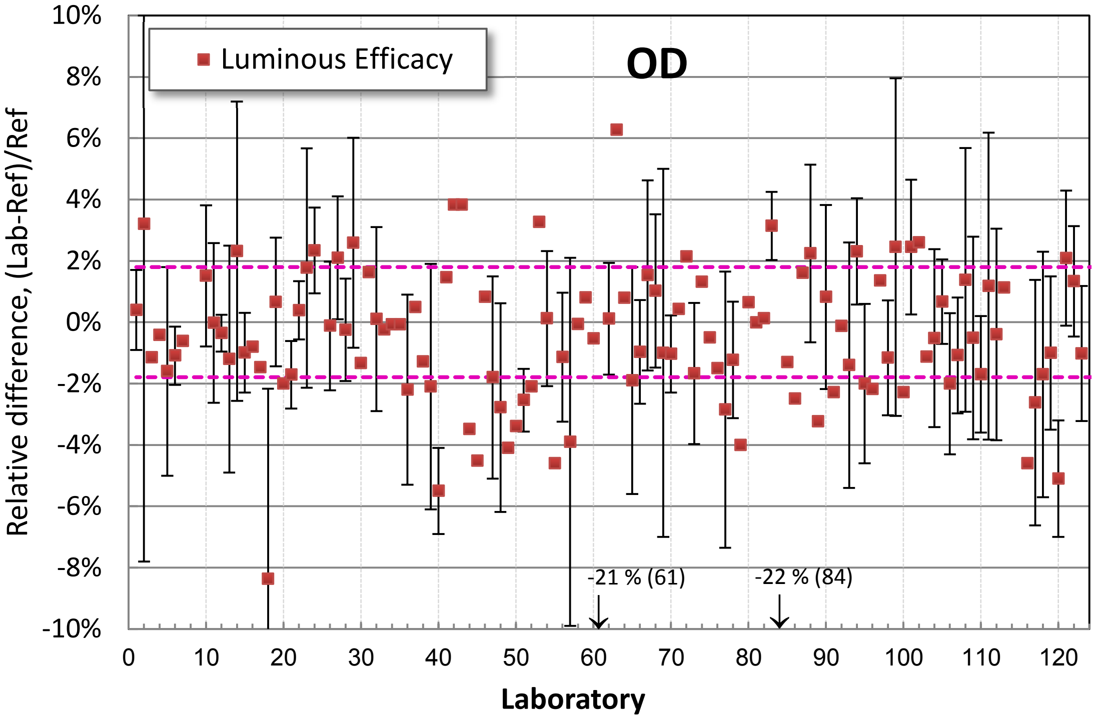

Figure 9-8. Relative differences of luminous efficacy for omnidirectional LED lamp (OD)

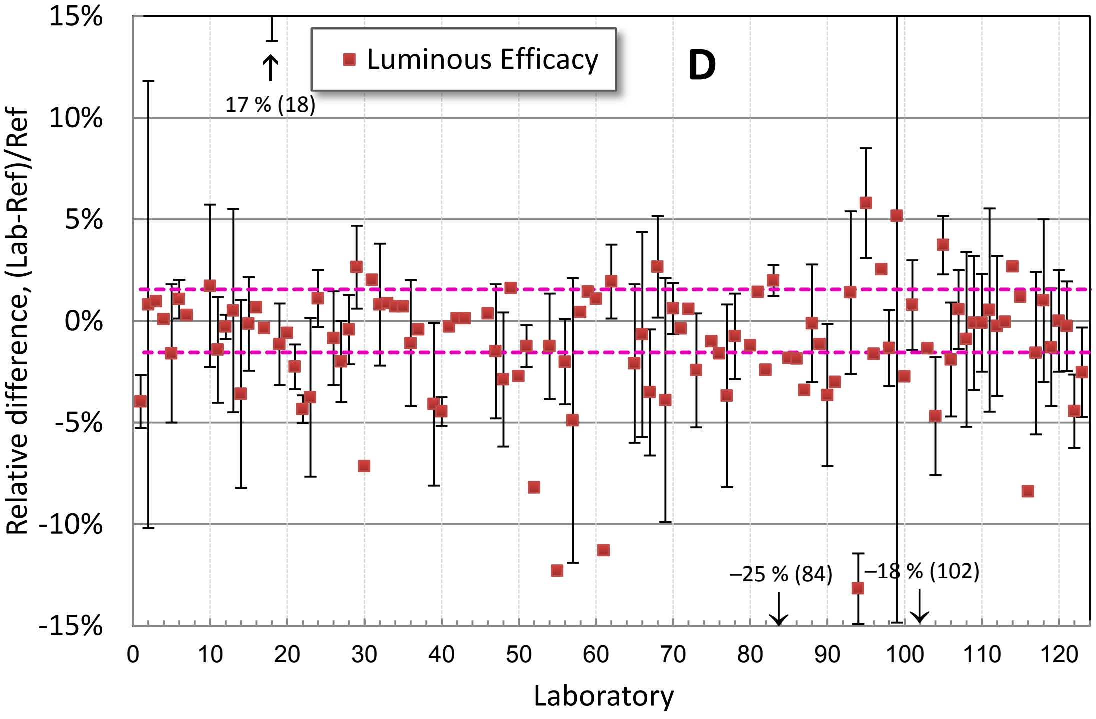

Figure 9-9. Relative differences of luminous efficacy for directional LED lamp (D)

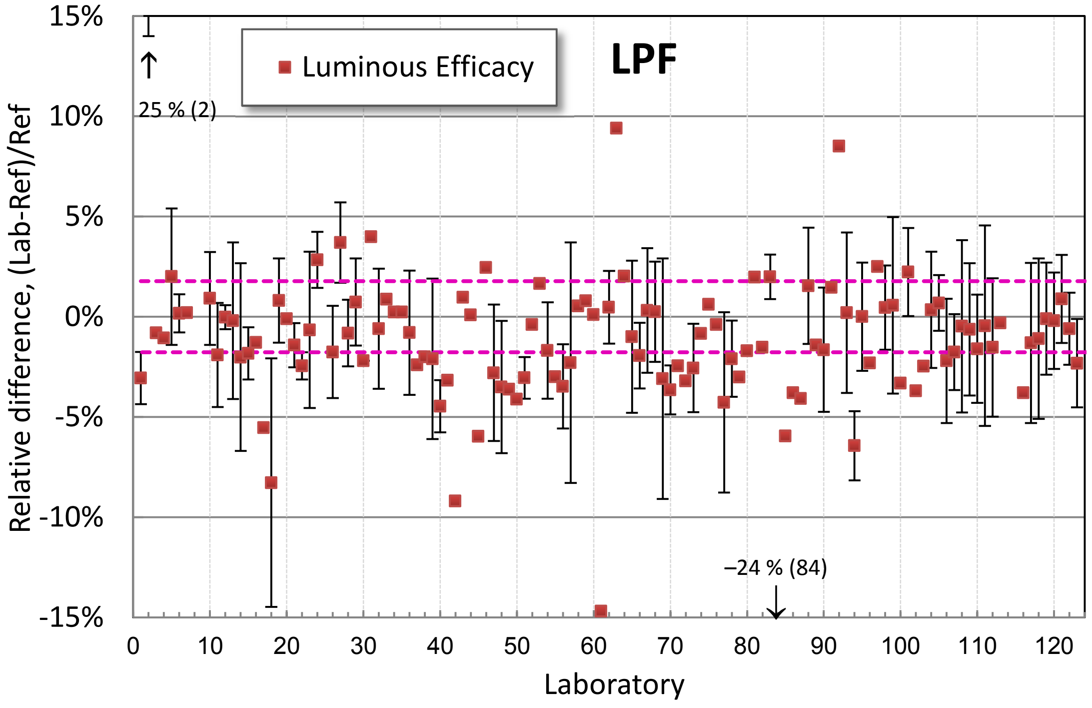

Figure 9-10. Relative differences of luminous efficacy for low power factor lamp (LPF)

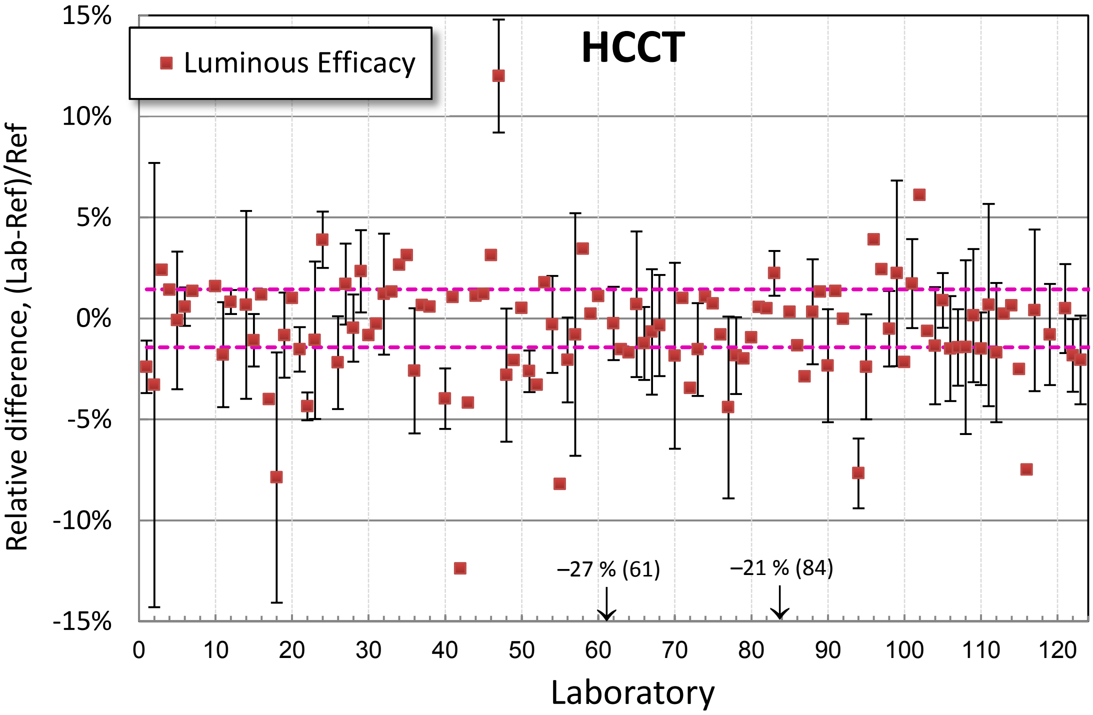

Figure 9-11. Relative differences of luminous efficacy for high CCT lamp (HCCT)

Figure 9-12 shows the summary of the relative differences of total luminous efficacy comparing artefact types, using robust standard deviation as described in Algorithm A, Annex C, ISO 13528:2005 [8]. Similar trends are observed as luminous flux in these results. The variations in measurements of the LED lamps (on the average) are 1.5 times larger than that for an incandescent lamp. There are no significant differences between the different types of LED lamps.

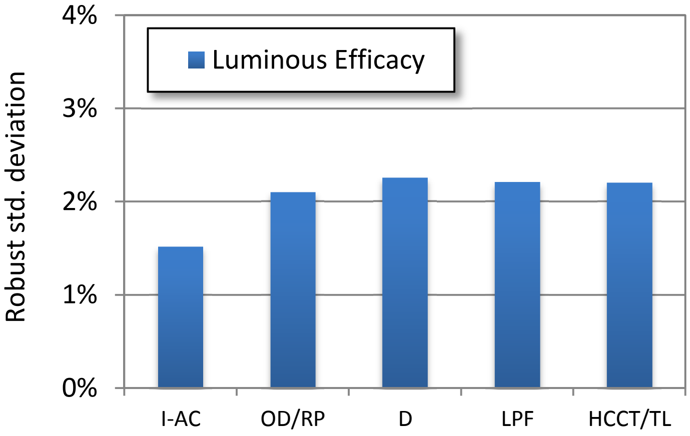

Figure 9-12. Summary of relative differences of luminous efficacy. The bars show the robust standard deviations of the relative differences of all laboratories for each type of lamp.

9.1.3 RMS current

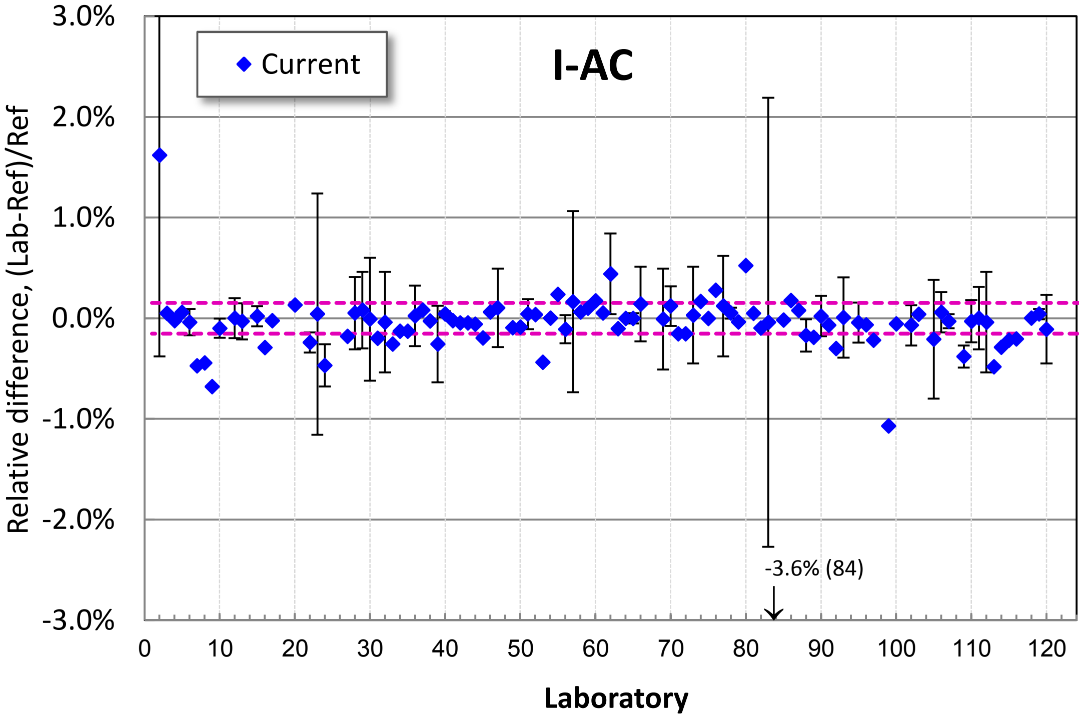

Figure 9-13. Relative differences of RMS current for Incandescent lamp AC operation (I-AC)

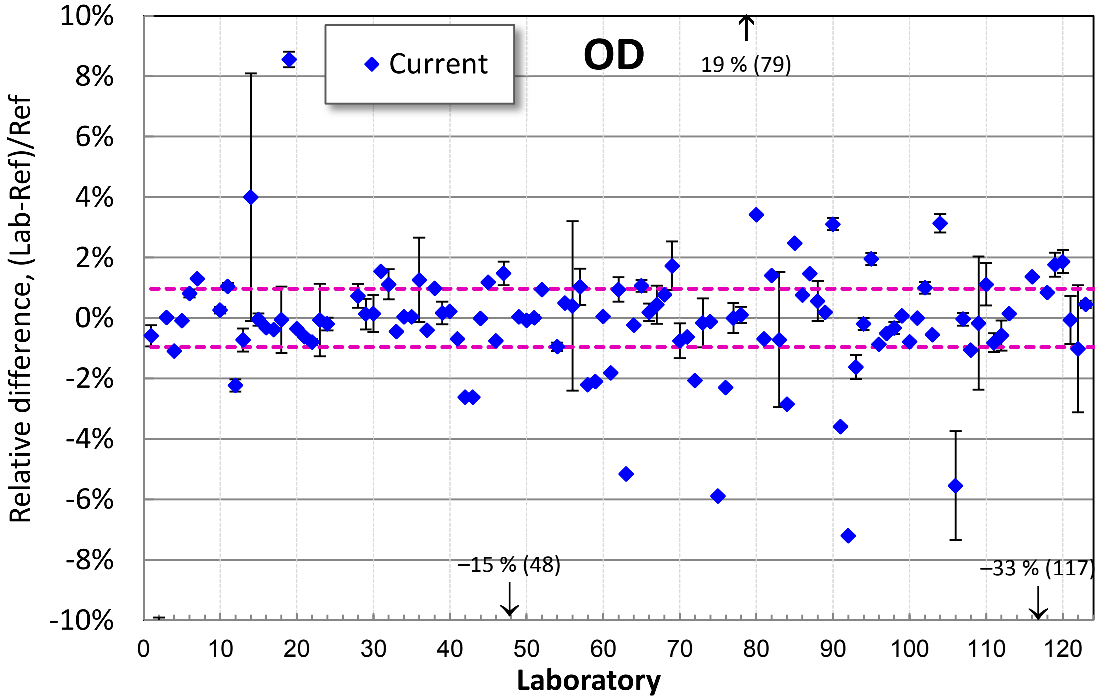

Figure 9-14. Relative differences of RMS current for omnidirectional LED lamp (OD)

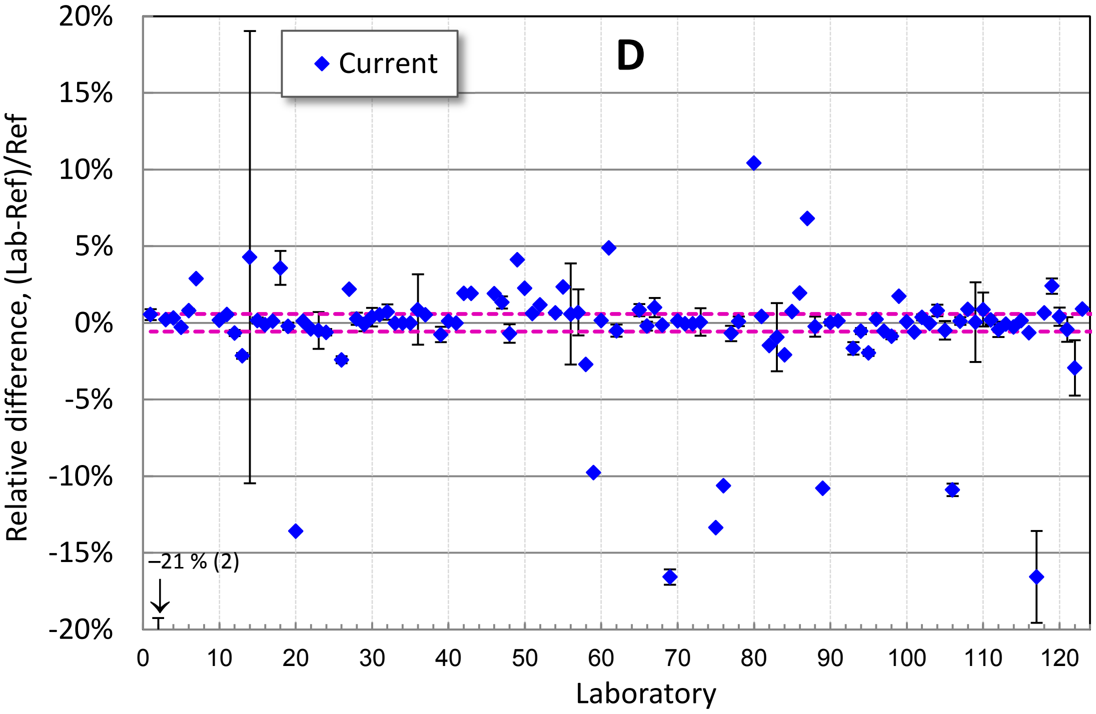

Figure 9-15. Relative differences of RMS current for directional LED lamp (D)

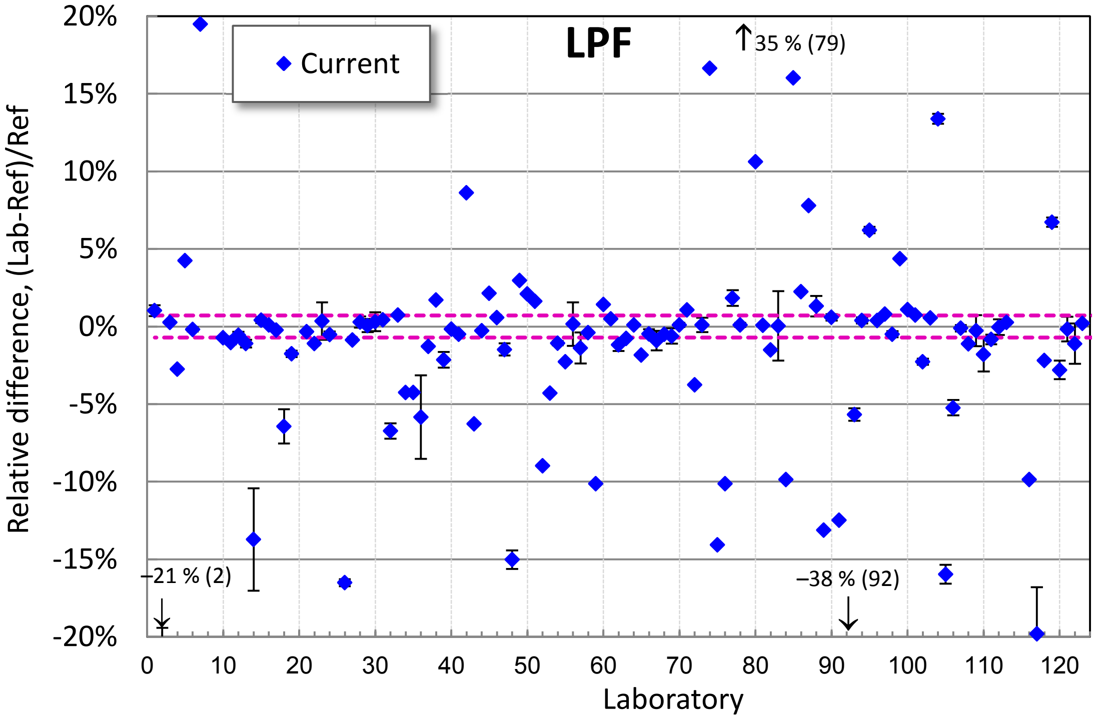

Figure 9-16. Relative differences of RMS current for low power factor lamp (LPF)

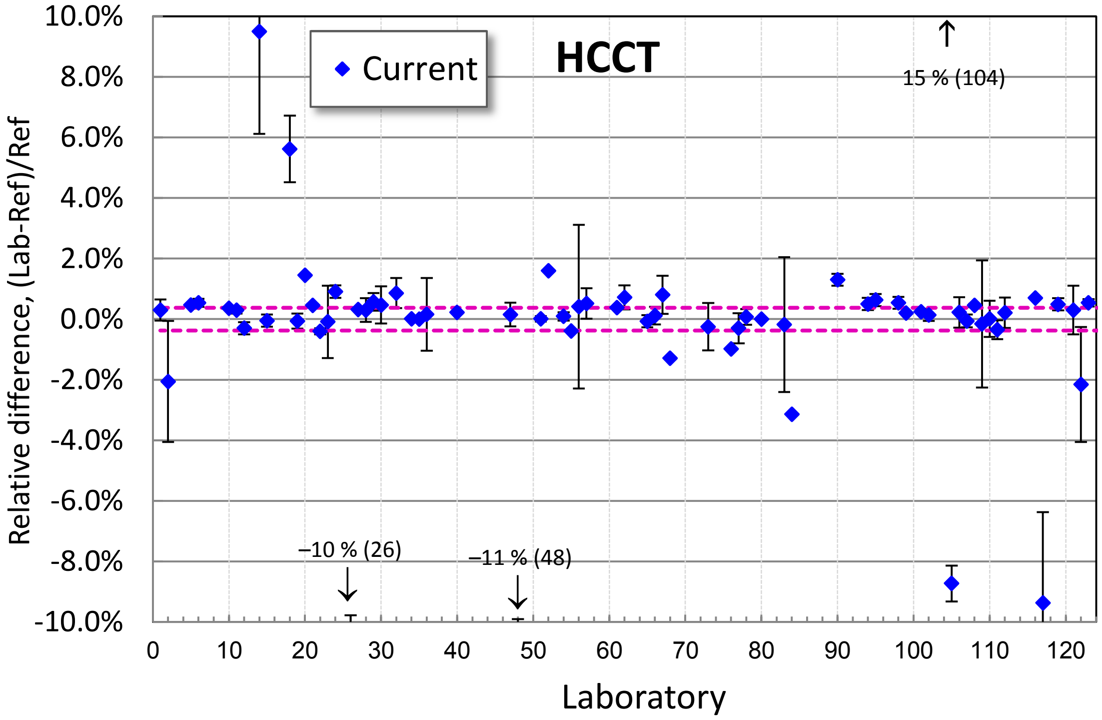

Figure 9-17. Relative differences of RMS current for high CCT lamp (HCCT). The data of NIST-HCCT are excluded in this figure since current is the set parameter for NIST-HCCT

Figure 9-18 shows the comparison of the variations in the results for RMS current for different artefact types, using robust standard deviation described in Algorithm A, Annex C, ISO 13528:2005 [8]. The variations of the LED lamps are significantly larger than those of the incandescent lamp by more than an order of magnitude. There are also large differences observed between the LED lamp types, and the variation in the measured results of the low power factor (LPF) lamp is significantly larger.

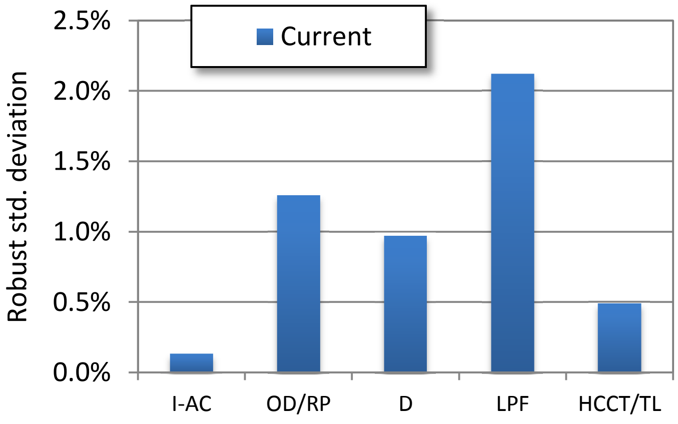

Figure 9-18. Summary of relative differences of RMS current. The bars show the robust standard deviations of the relative differences of all laboratories for each type of lamp

9.1.4 Active Power

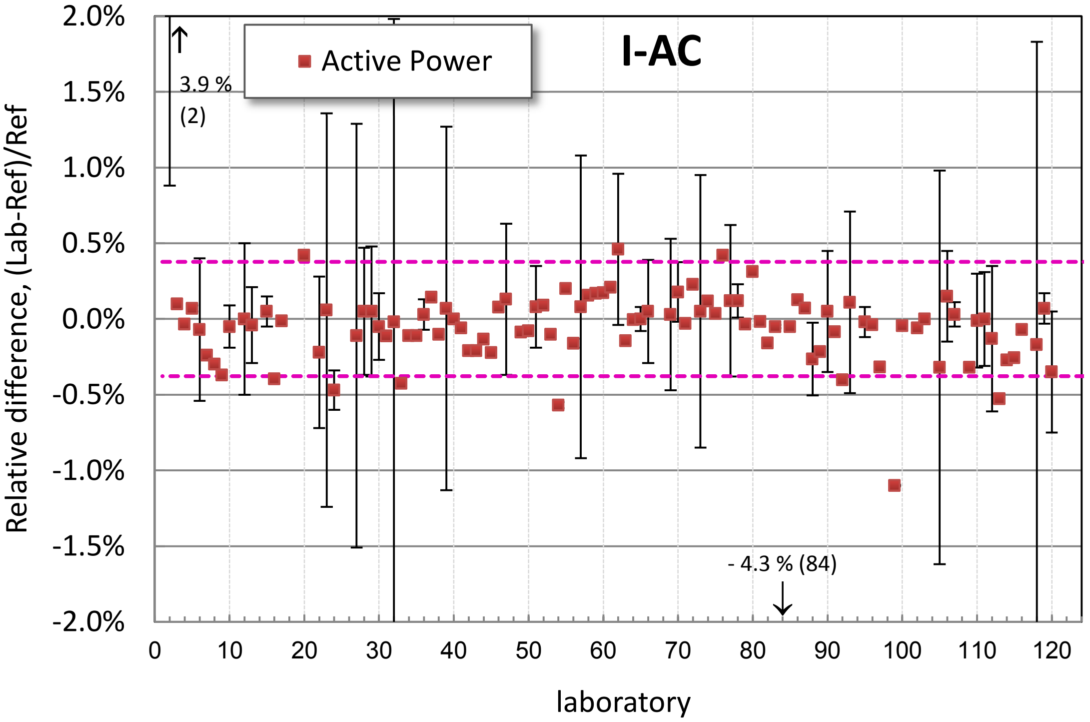

Figure 9-19. Relative differences of active power for Incandescent lamp AC operation (I-AC)

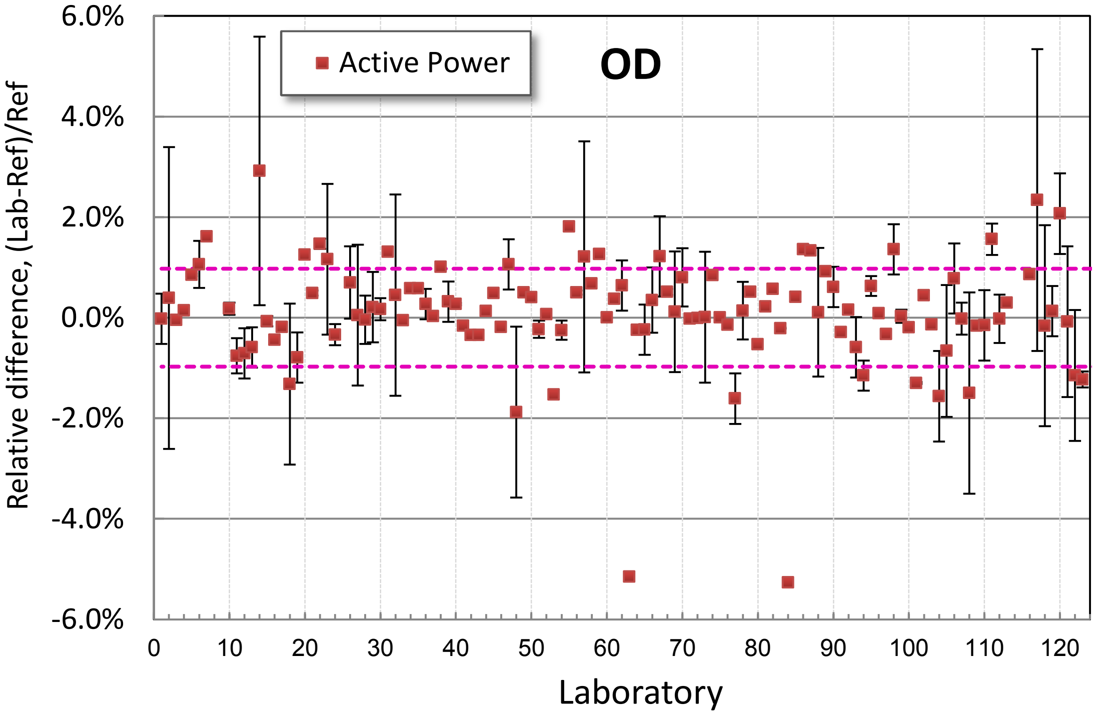

Figure 9-20. Relative differences of active power for omnidirectional LED lamp (OD)

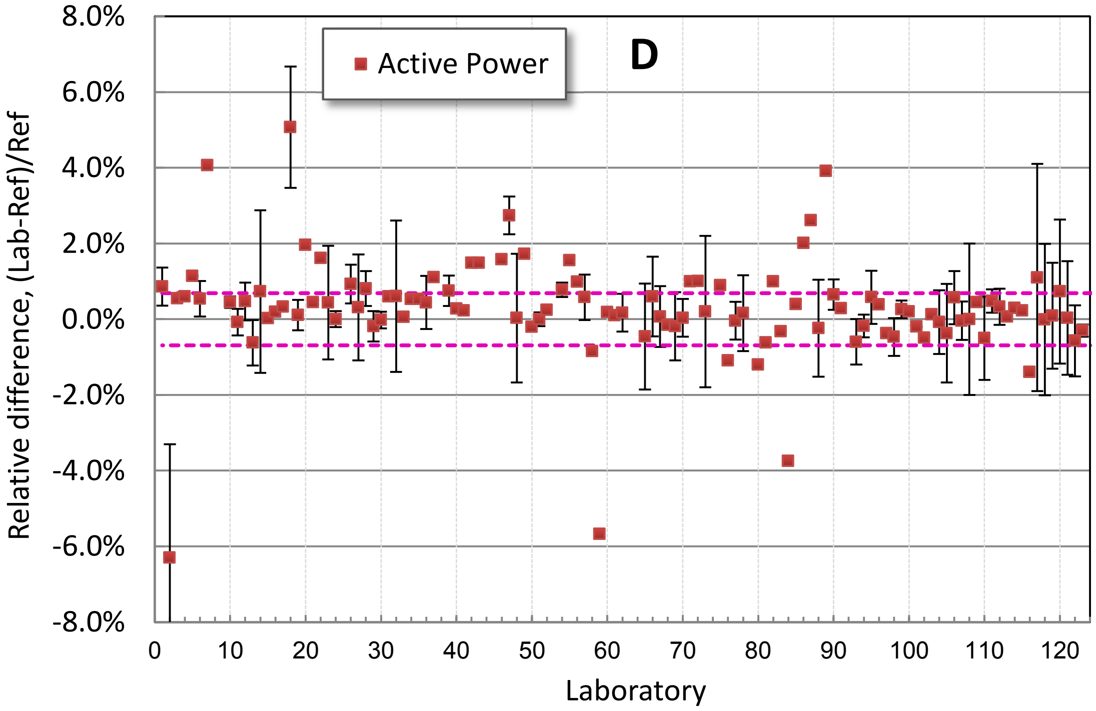

Figure 9-21. Relative differences of active power for directional LED lamp (D)

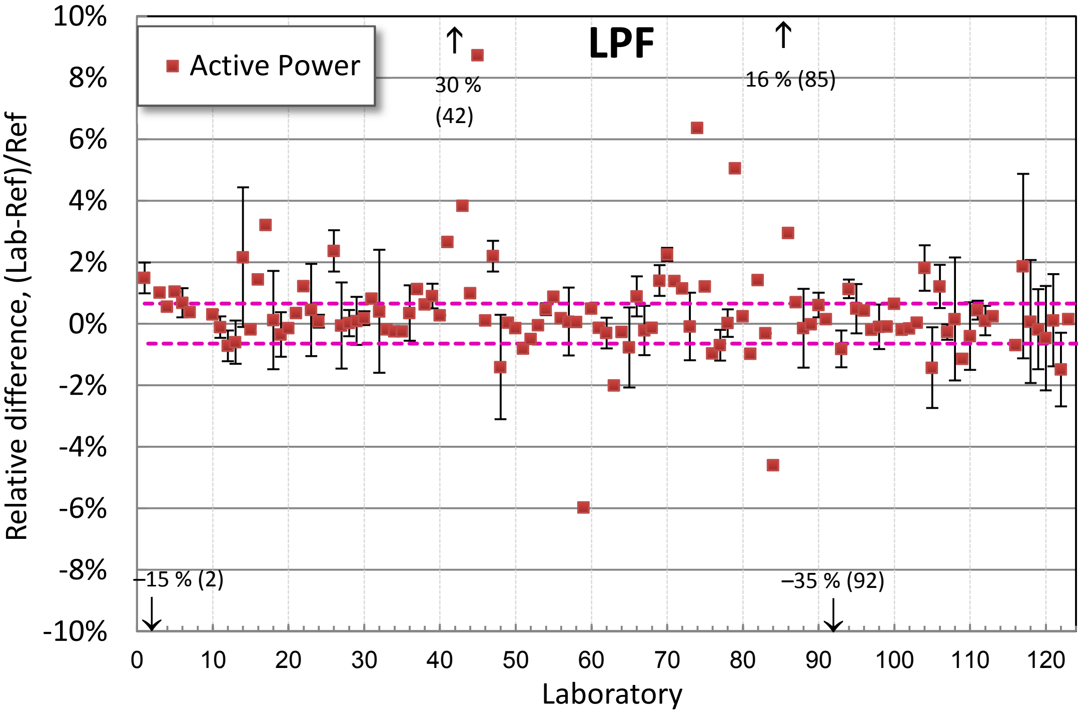

Figure 9-22. Relative differences of active power for lower power factor lamp (LPF)

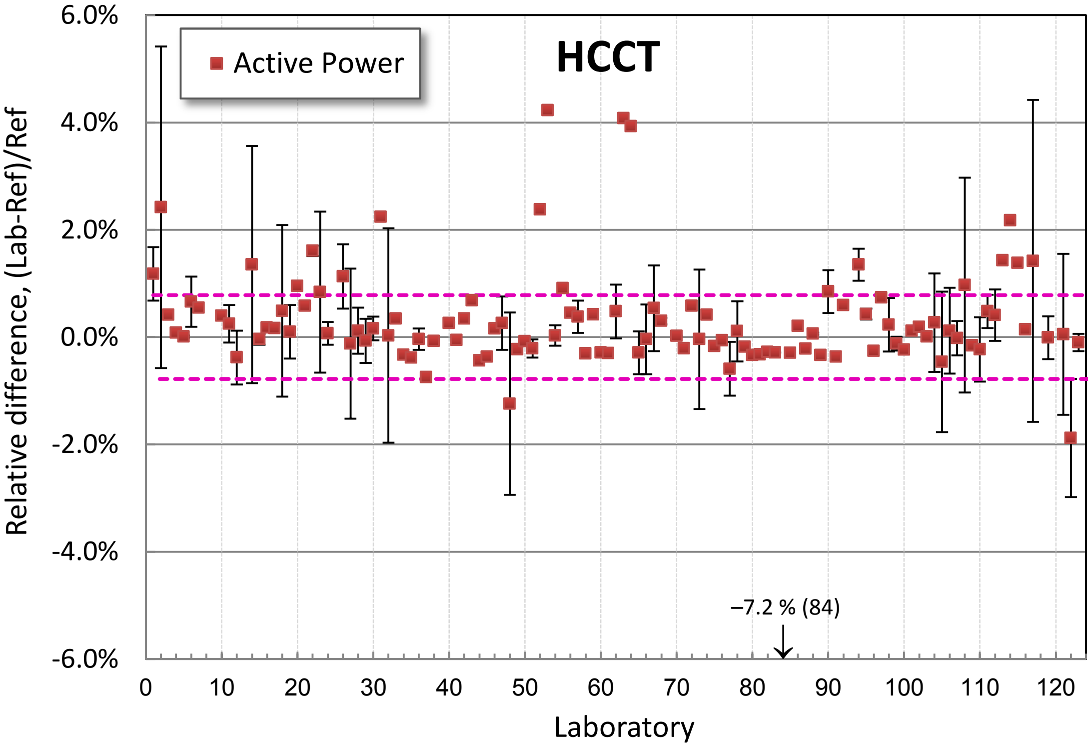

Figure 9-23. Relative differences of active power for high CCT lamp (HCCT)

Figure 9-24 shows the comparison of the variations in the results for active power for different artefact types, using robust standard deviation as described in Algorithm A, Annex C, ISO 13528:2005 [8]. The variations in the measurements of the LED lamps (on average) are about 3 to 4 times larger than those of the incandescent lamp. The variation in the measurement of the low power factor (LPF) lamp is the largest of the LED lamps.

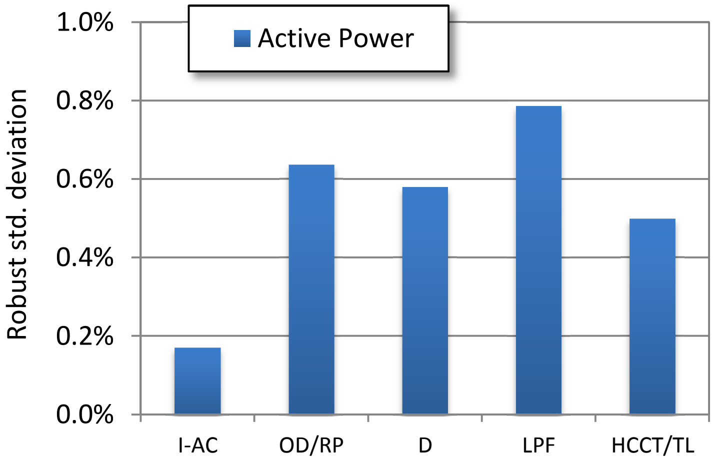

Figure 9-24. Summary of relative differences of active power. The bars show the robust standard deviations of the relative differences of all laboratories for each type of lamp

9.1.5 Chromaticity x

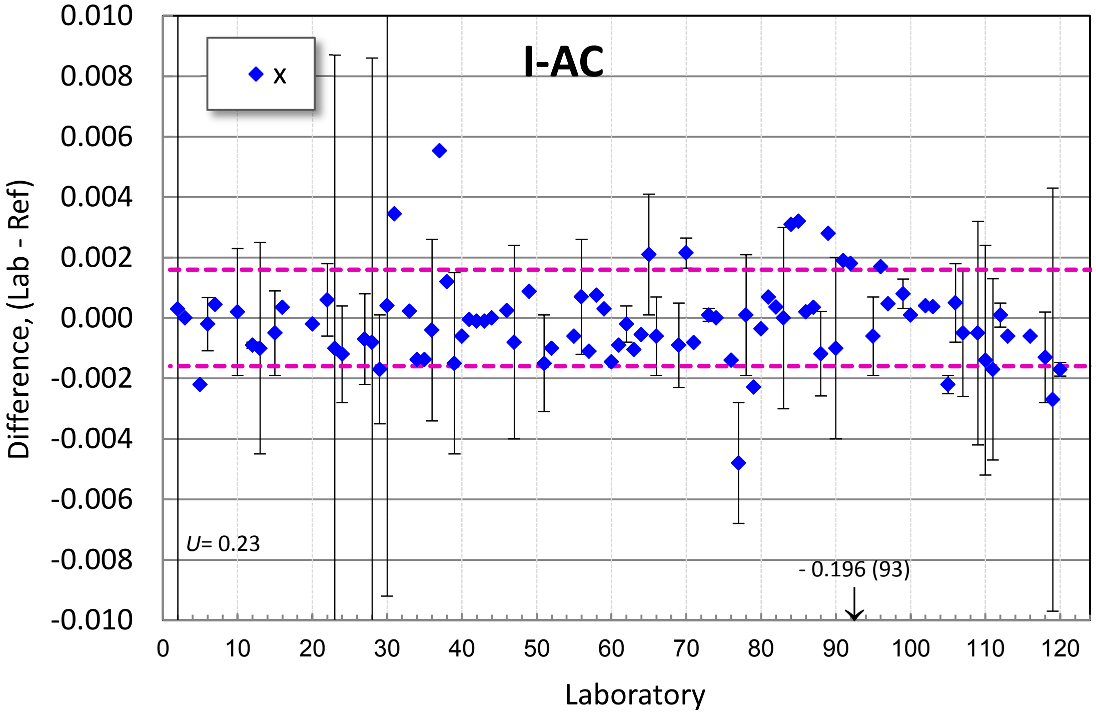

Figure 9-25. Differences of chromaticity x for Incandescent lamp AC operation (I-AC)

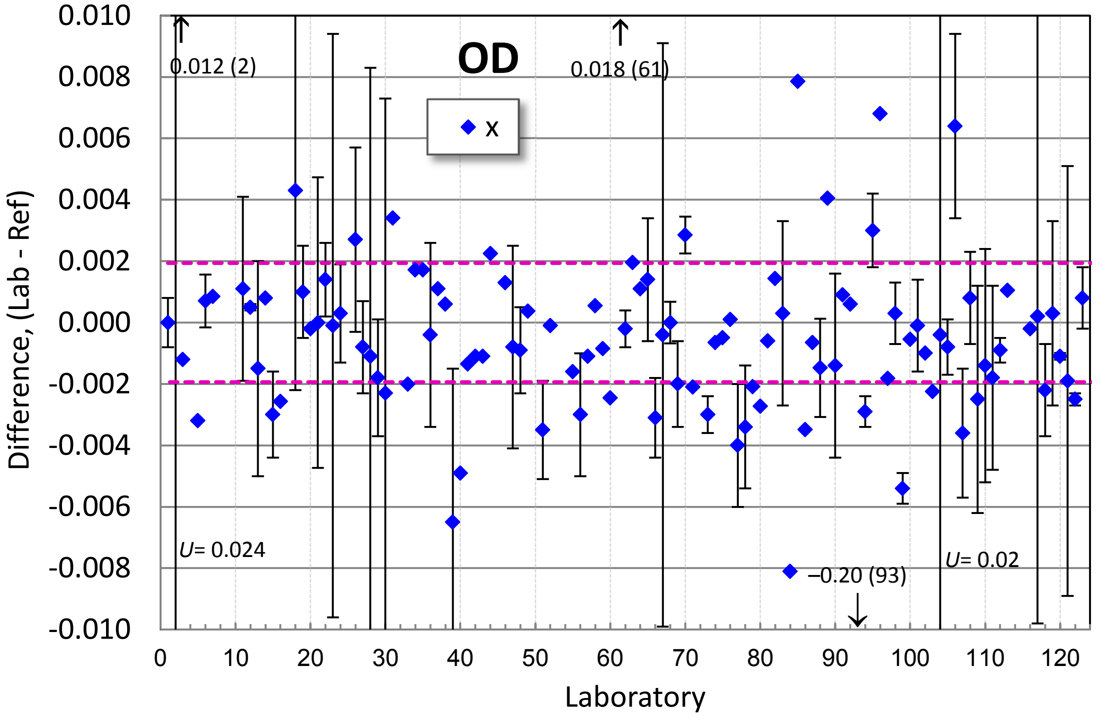

Figure 9-26. Differences of chromaticity x for omnidirectional LED lamp (OD)

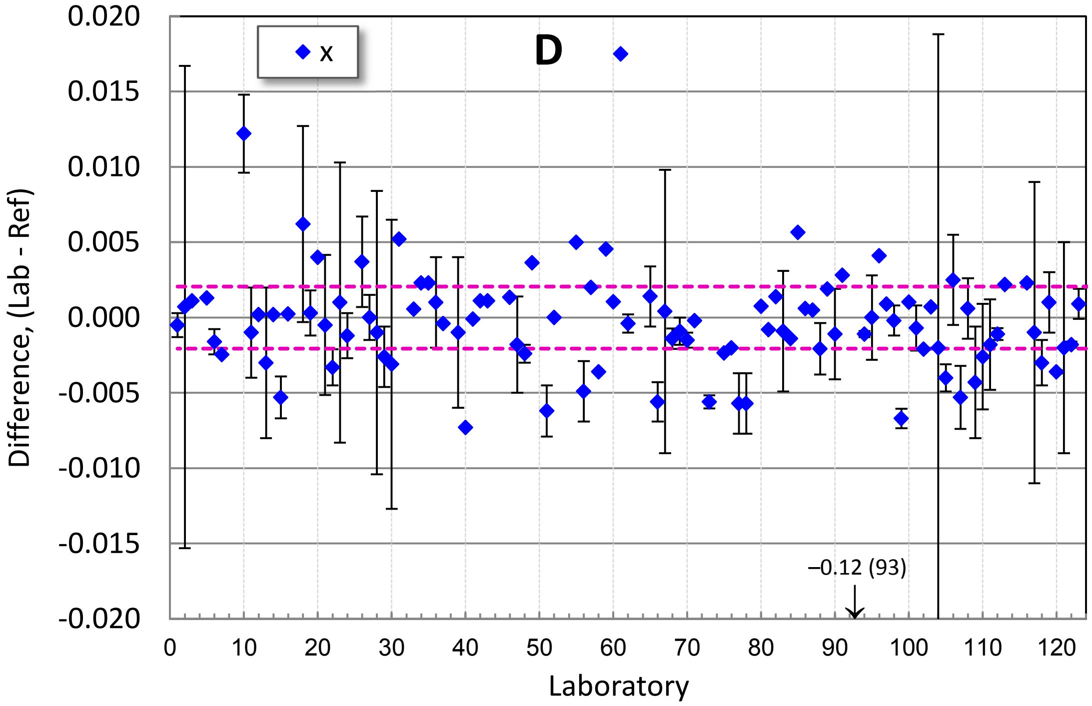

Figure 9-27. Differences of chromaticity x for directional LED lamp (D)

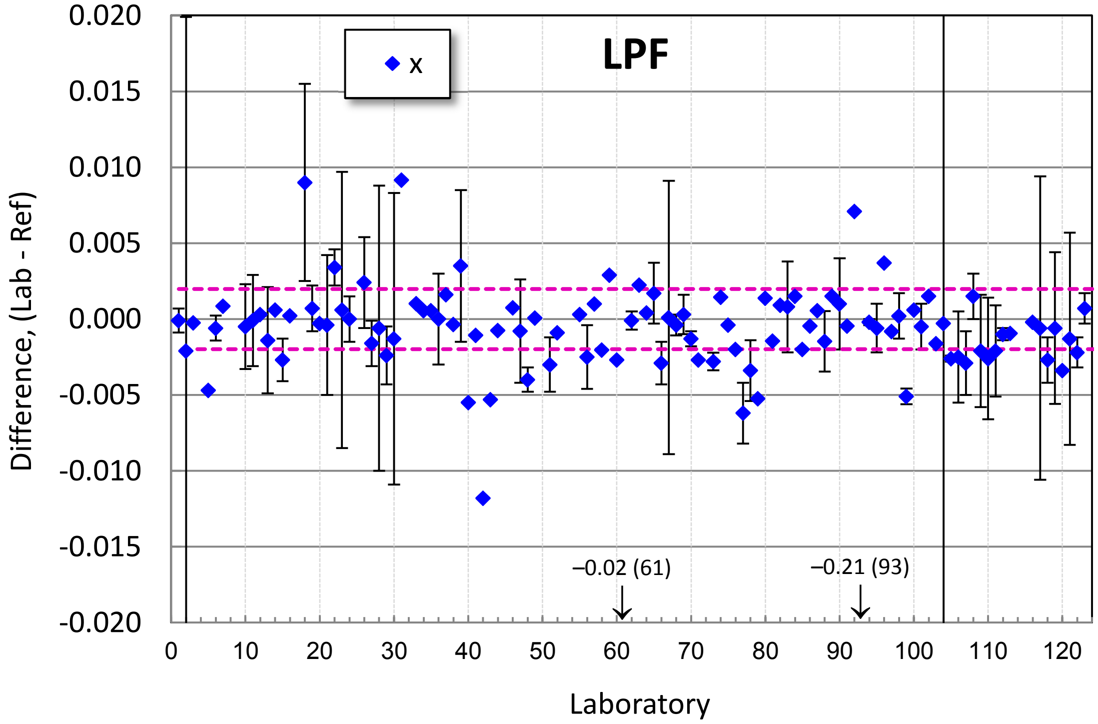

Figure 9-28. Differences of chromaticity x for low power factor lamp (LPF)

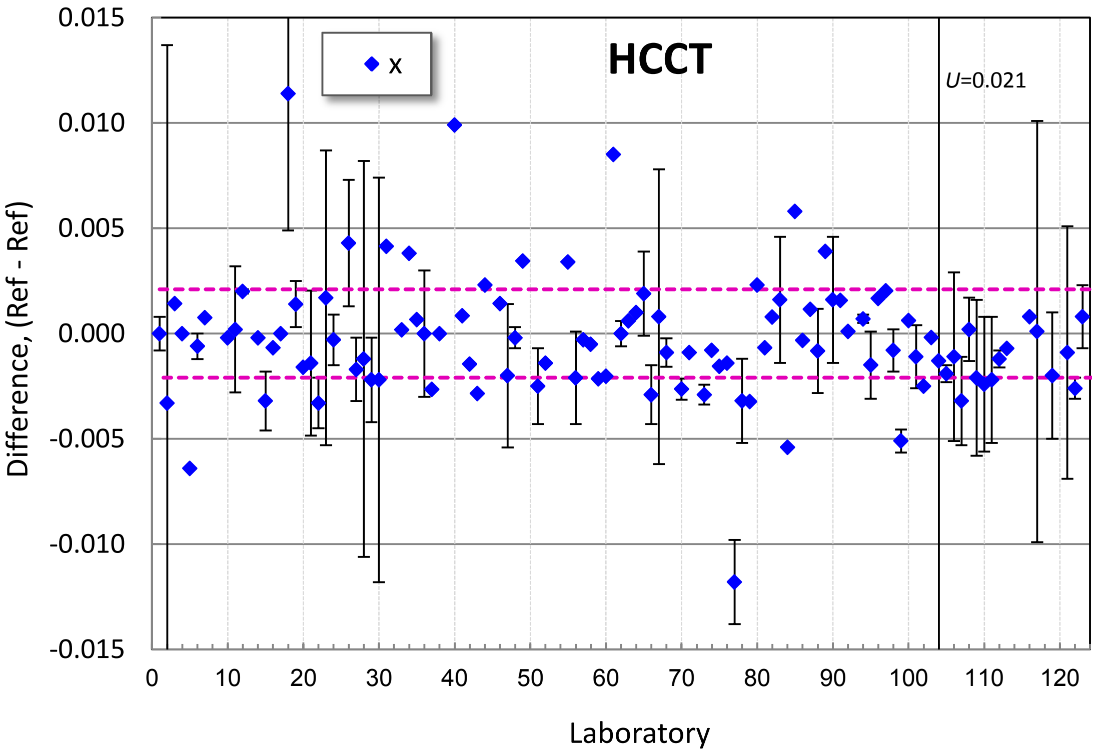

Figure 9-29. Differences of chromaticity x for high CCT lamp (HCCT)

Figure 9-30 shows the comparison of the variations in the results for chromaticity x for different artefact types, using robust standard deviation as described in Algorithm A, Annex C, ISO 13528:2005 [8]. The variations in LED lamp measurements (on average) are about 2 times larger than those for the incandescent lamps. The differences between the different LED lamp types are not significant.

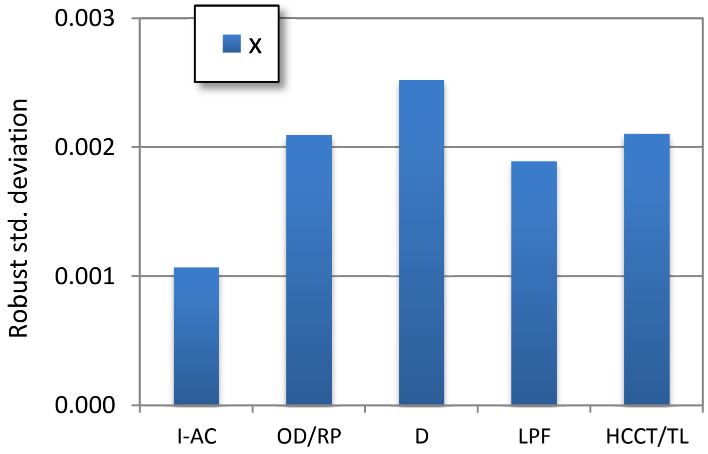

Figure 9-30. Summary of differences of chromaticity x. The bars show the robust standard deviations of the differences of all laboratories for each type of lamp

9.1.6 Chromaticity y

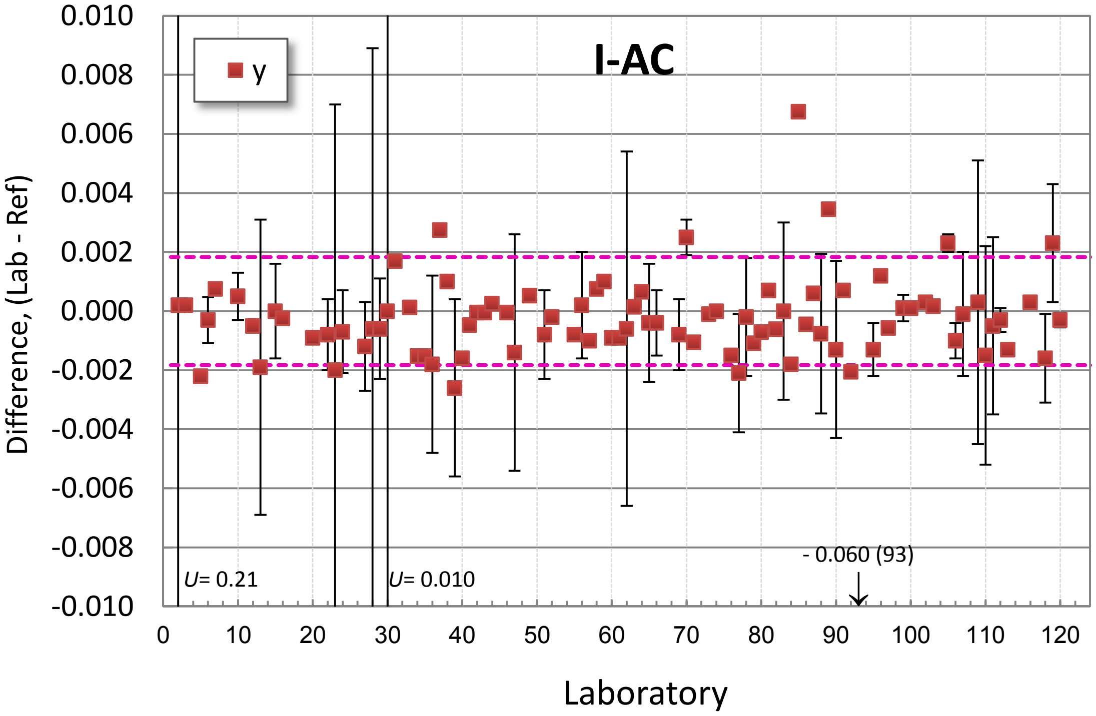

Figure 9-31. Differences of chromaticity y for Incandescent lamp AC operation (I-AC)

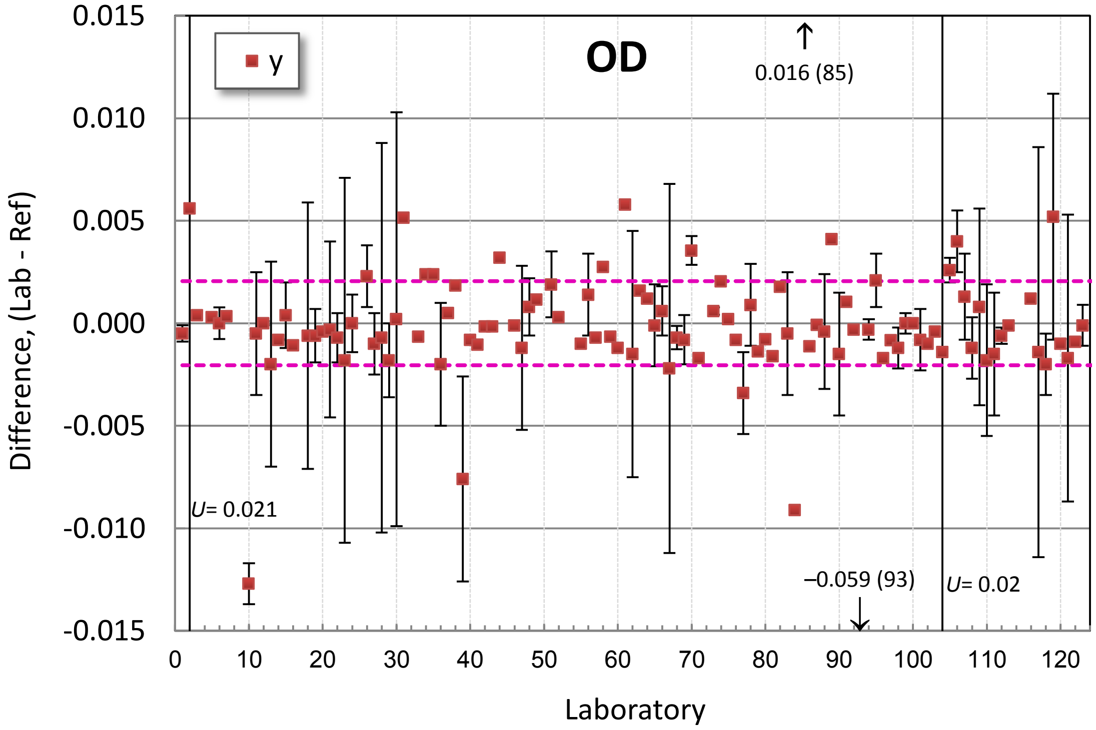

Figure 9-32. Differences of chromaticity y for omnidirectional LED lamp (OD)

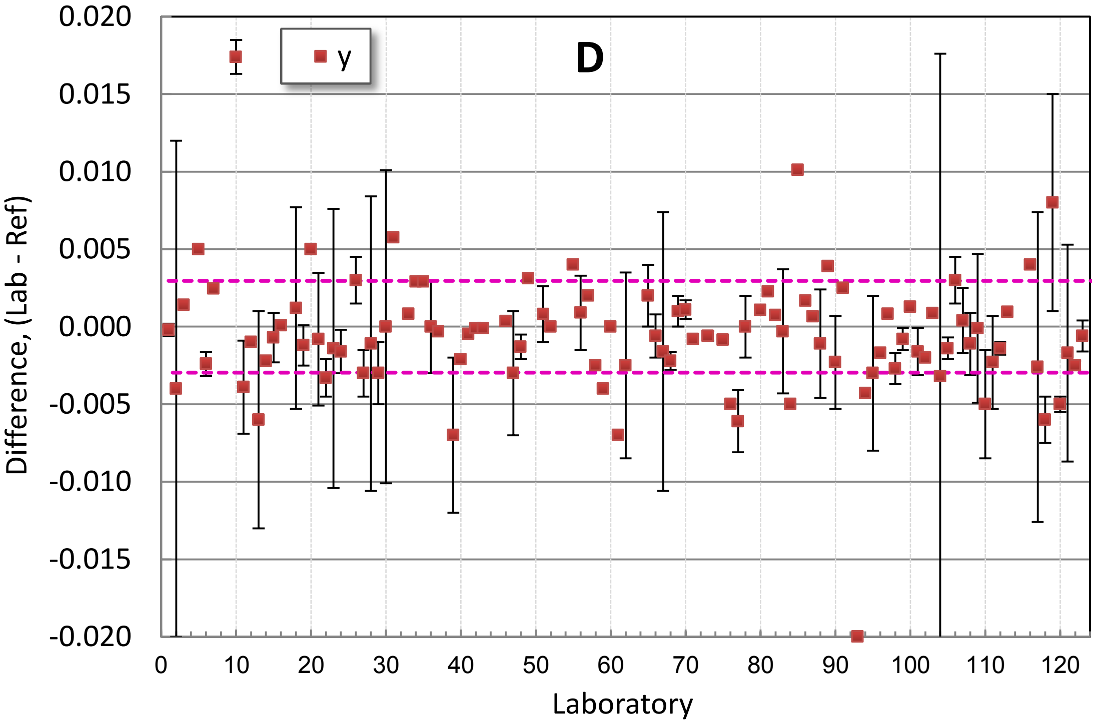

Figure 9-33. Differences of chromaticity y for directional LED lamp (D)

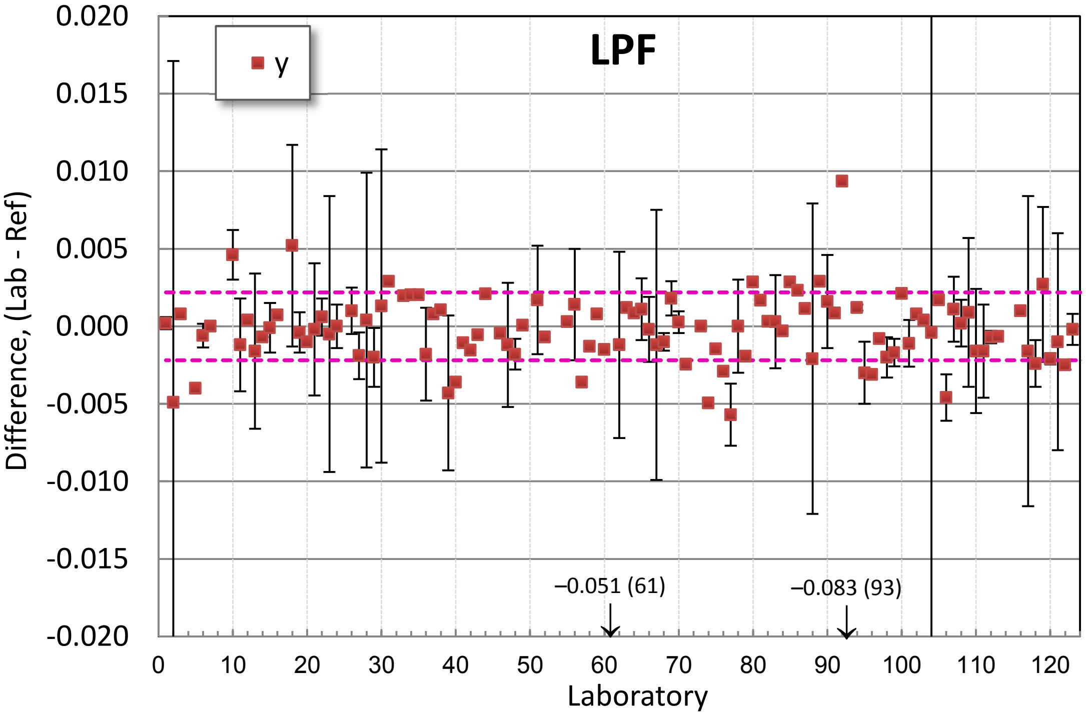

Figure 9-34. Differences of chromaticity y for low power factor lamp (LPF)

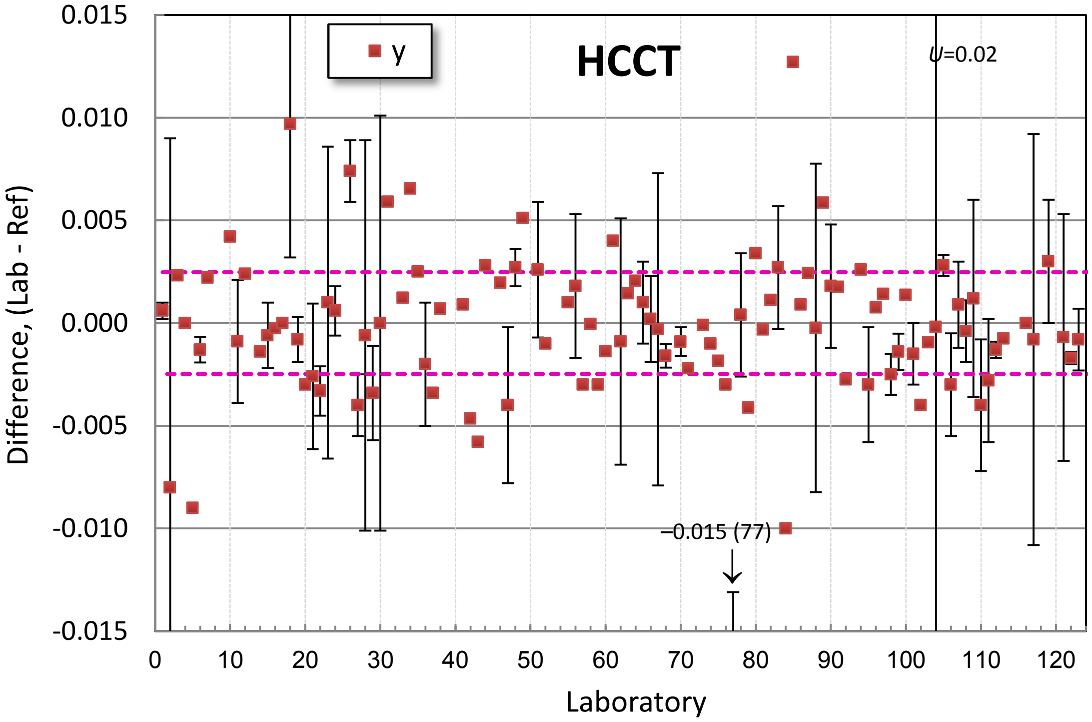

Figure 9-35. Differences of chromaticity y for high CCT lamp (HCCT)

Figure 9-36 shows the comparison of the variations in the results for chromaticity y for different artefact types, using robust standard deviation as described in Algorithm A, Annex C, ISO 13528:2005 [8]. The variations in the measurements of the LED lamps (on average) are 2.2 times larger than those for the incandescent lamp.

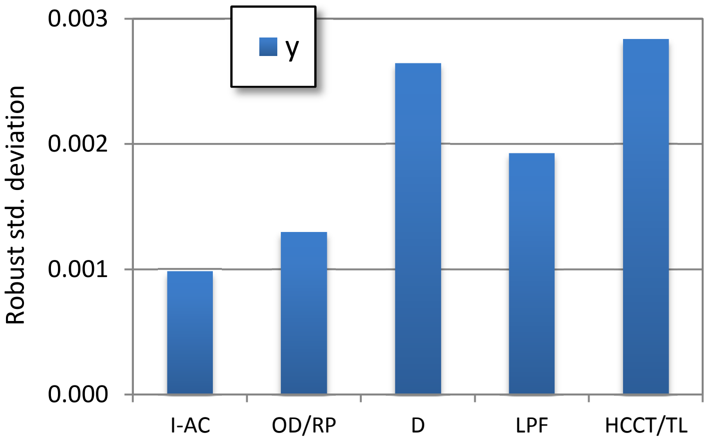

Figure 9-36. Summary of the differences of chromaticity y. The bars show the robust standard deviations of the differences of all laboratories for each type of lamp

9.1.7 Correlated Colour Temperature (CCT)

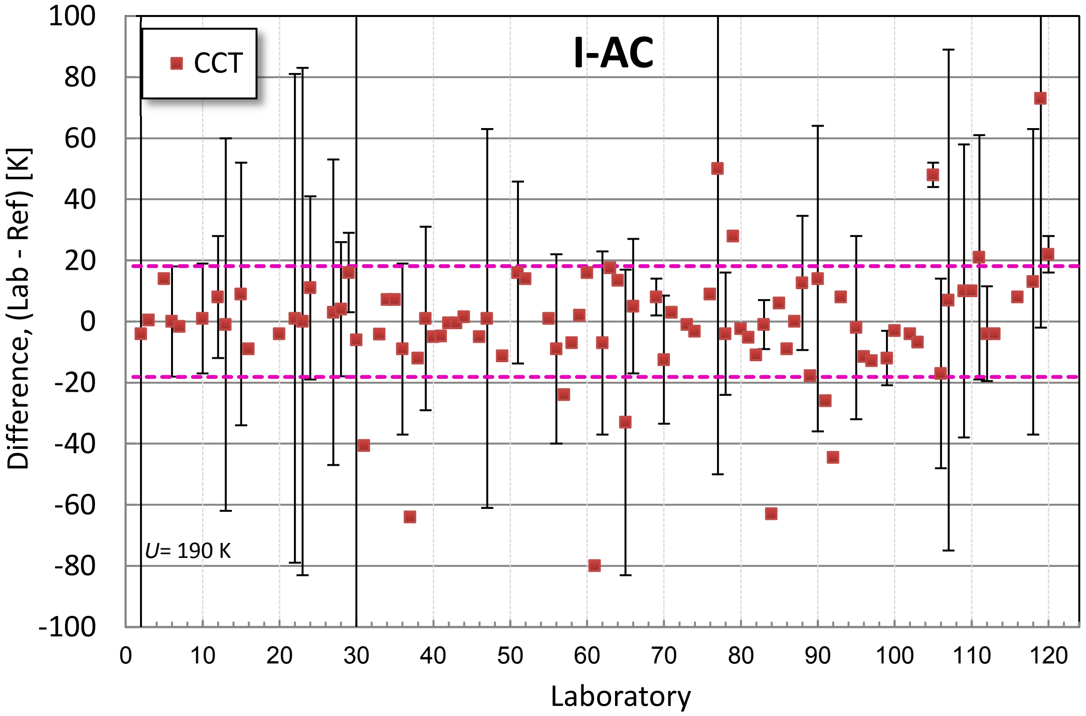

Figure 9-37. Differences of CCT for Incandescent lamp AC operation (I-AC)

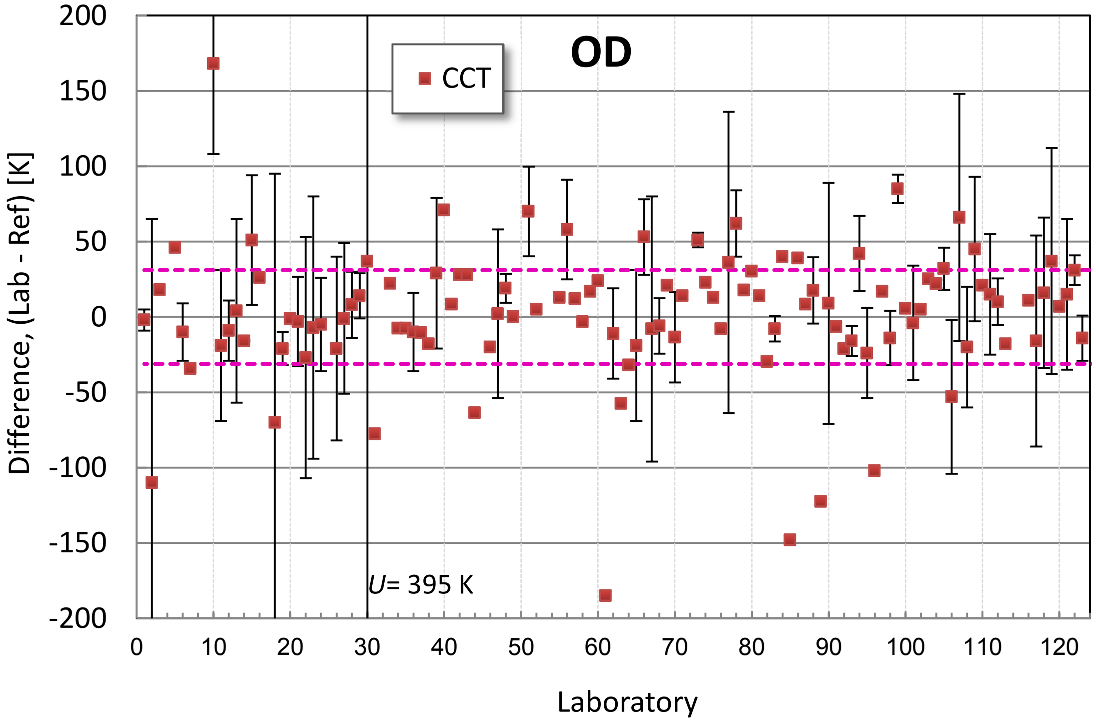

Figure 9-38. Differences of CCT for omnidirectional LED lamp (OD)

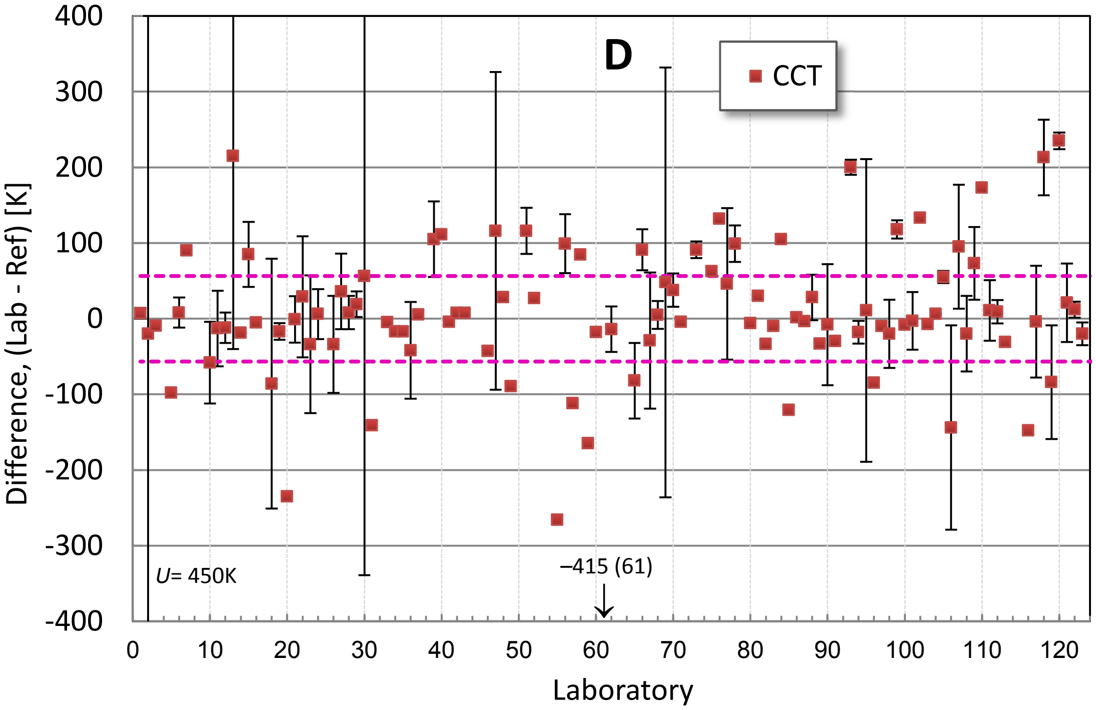

Figure 9-39. Differences of CCT for directional LED lamp (D)

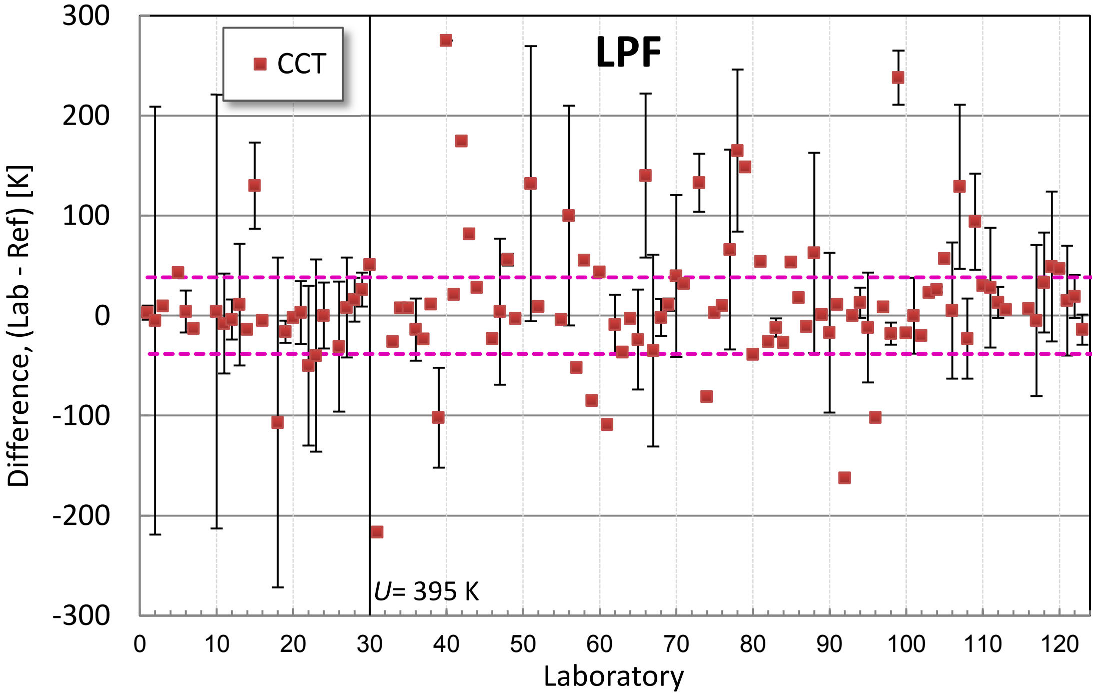

Figure 9-40. Differences of CCT for low power factor lamp (LPF)

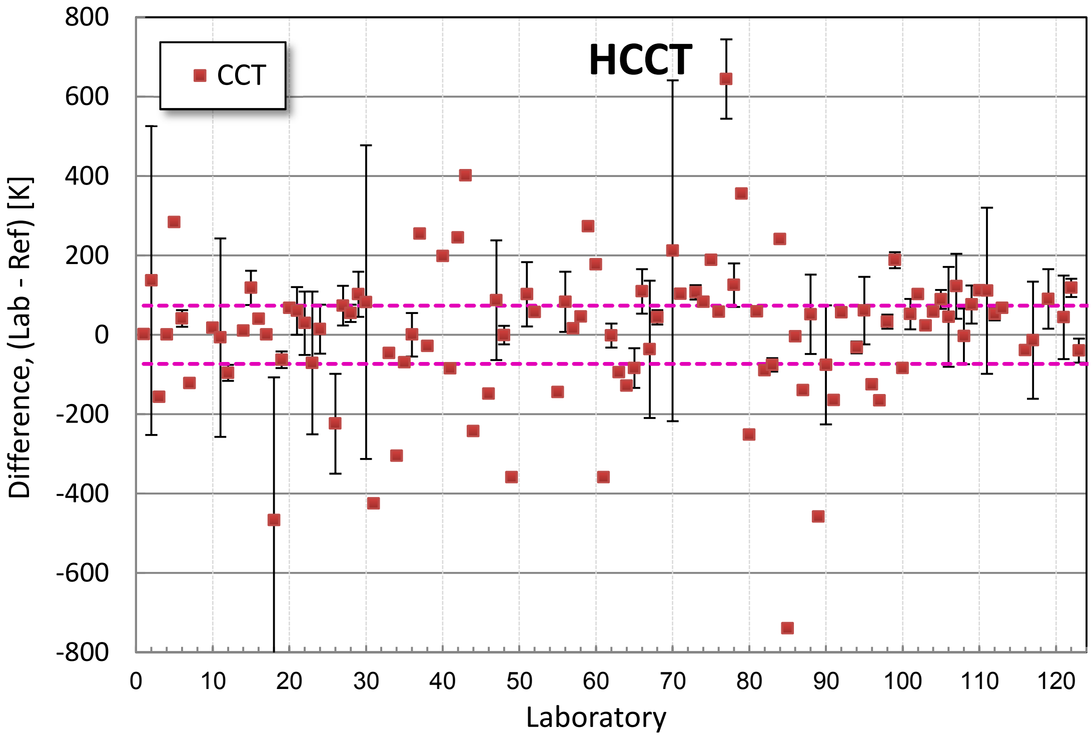

Figure 9-41. Differences of CCT for high CCT lamp (HCCT)

Figure 9-42 shows comparison of the variations in the results for CCT for different artefact types, using robust standard deviation as described in Algorithm A, Annex C, ISO 13528:2005 [8]. The variations in LED lamps (on average, except HCCT lamp) are about 3 times larger than the incandescent lamp. And due to nonlinearity of the CCT scale, the variation in CCT normally increases, e.g., approximately 2.5 times from 3000 K to 6000 K, thus the larger deviation of the HCCT LED lamp shown in the figure is normal.

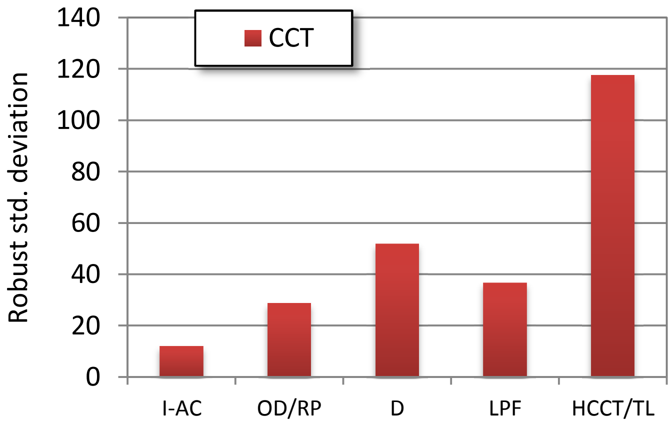

Figure 9-42. Summary of the differences of CCT. The bars show the robust standard deviations of the differences of all laboratories for each type of lamp

9.1.8 Colour Rendering Index (CRI) R_a

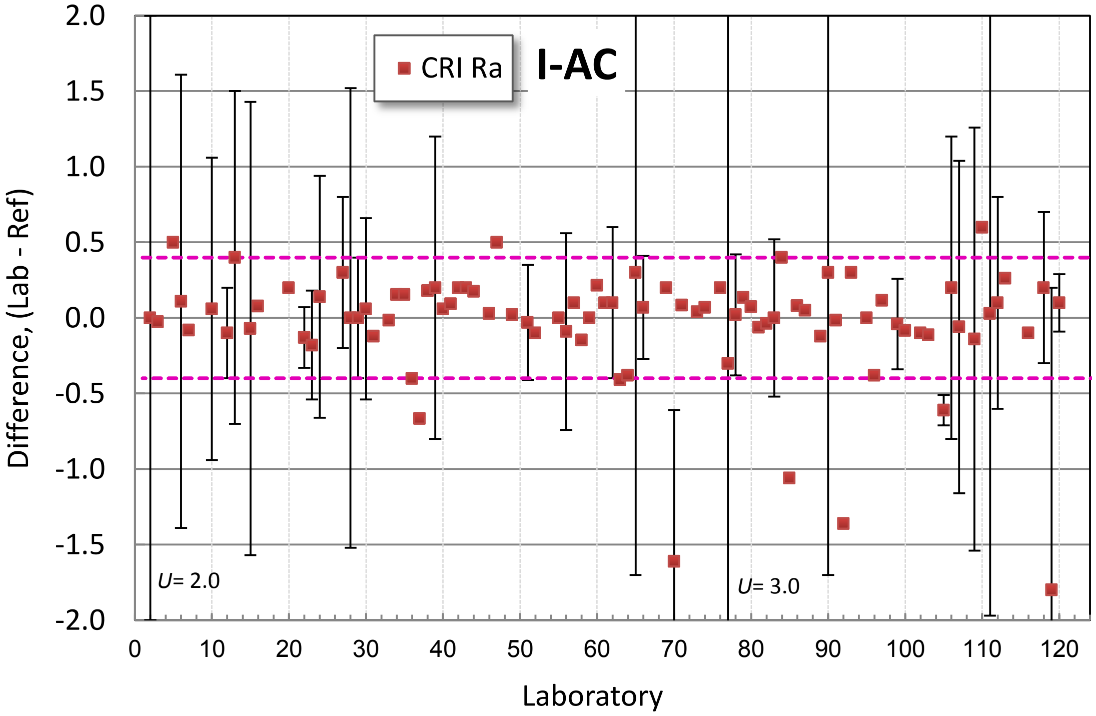

Figure 9-43. Differences of CRI R_a for Incandescent lamp AC operation (I-AC)

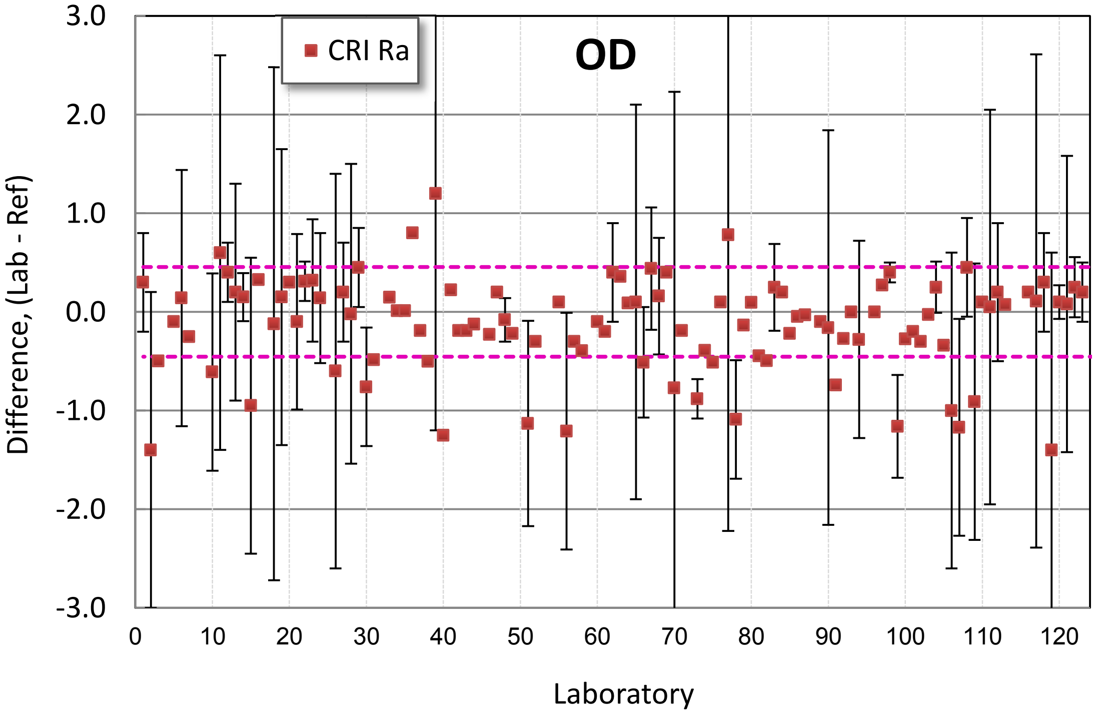

Figure 9-44. Differences of CRI R_a for omnidirectinoal LED lamp (OD)

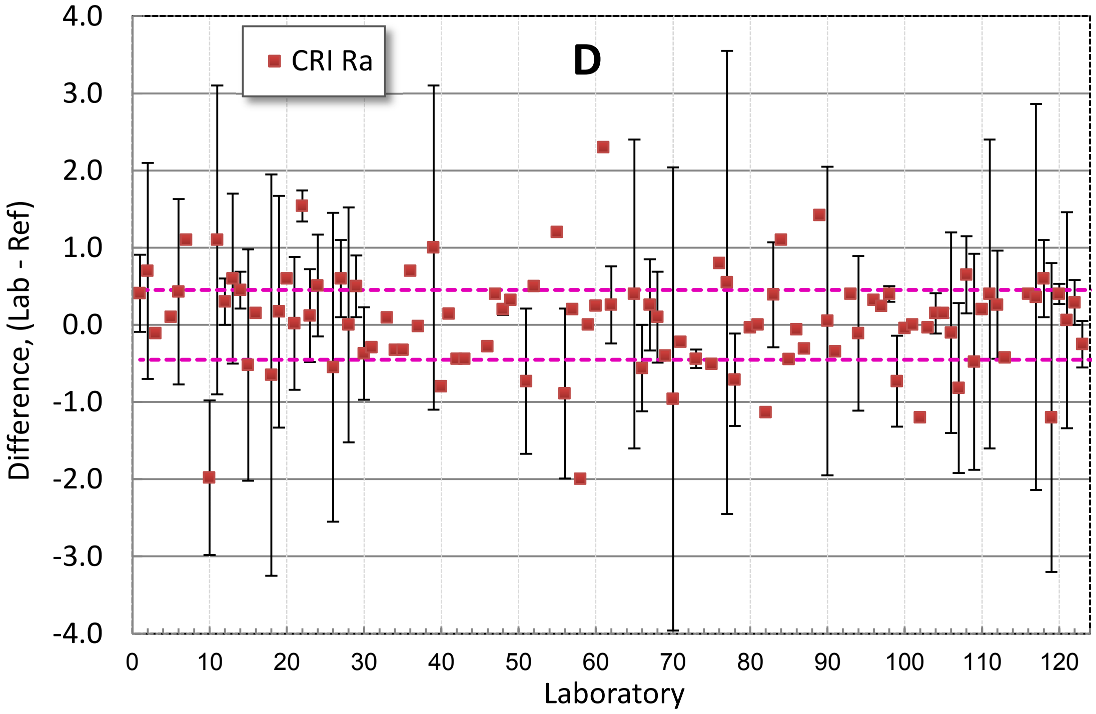

Figure 9-45. Differences of CRI R_a for directional LED lamp (D)

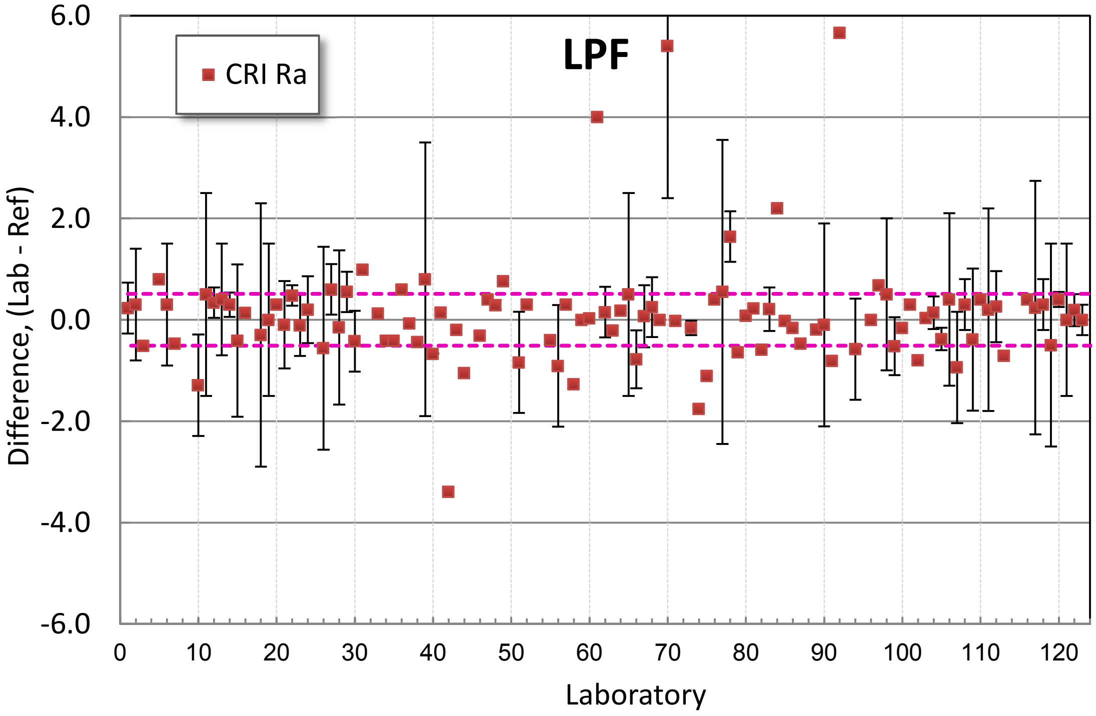

Figure 9-46. Differences of CRI R_a for low power factor lamp (LPF)

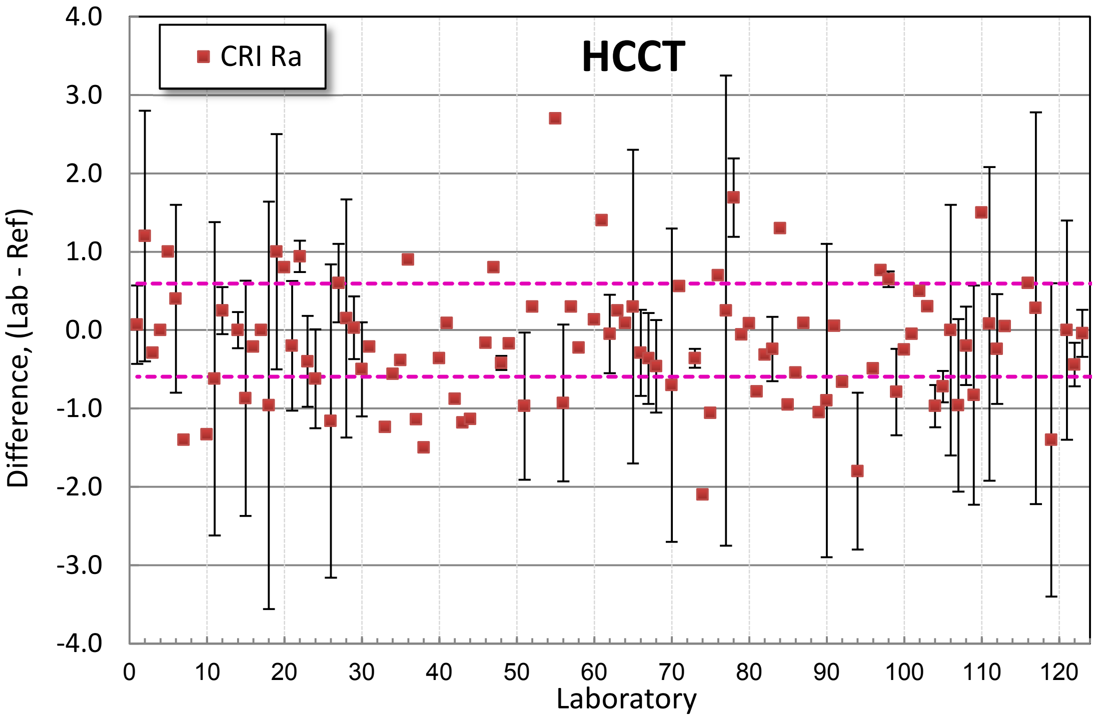

Figure 9-47. Differences of CRI R_a for high CCT lamp (HCCT)

Figure 9-48 shows comparison of the variations in the results for CRI R_a for different artefact types, using robust standard deviation as described in Algorithm A, Annex C, ISO 13528:2005 [8]. Variation in CRI R_a normally does not depend on CCT, thus the larger observed variation in the HCCT lamp measurements in this result is notable. This variation may be explained by the fact that the difference between the spectral distribution of the lamp used to calibrate a spectroradiometers (usually a tungsten halogen lamp) and the artefacts tested is greatest for a high CCT lamp than for a low CCT lamp, which causes larger errors e.g., from stray light of the spectroradiometer.

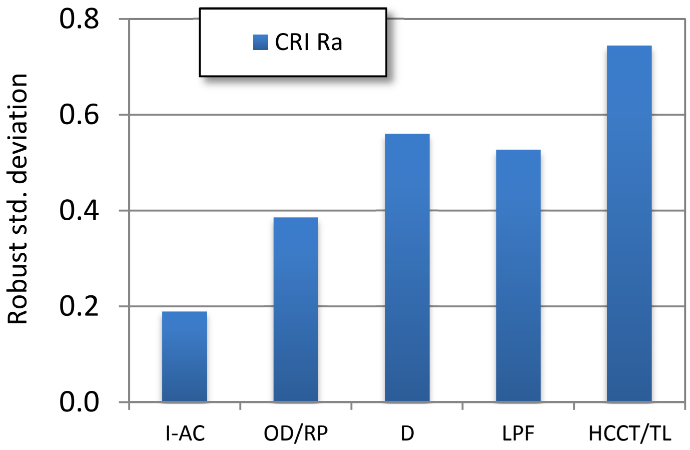

Figure 9-48. Summary of the differences of CRI R_a. The bars show the robust standard deviations of the differences of all laboratories for each type of lamp

9.1.9 Power factor

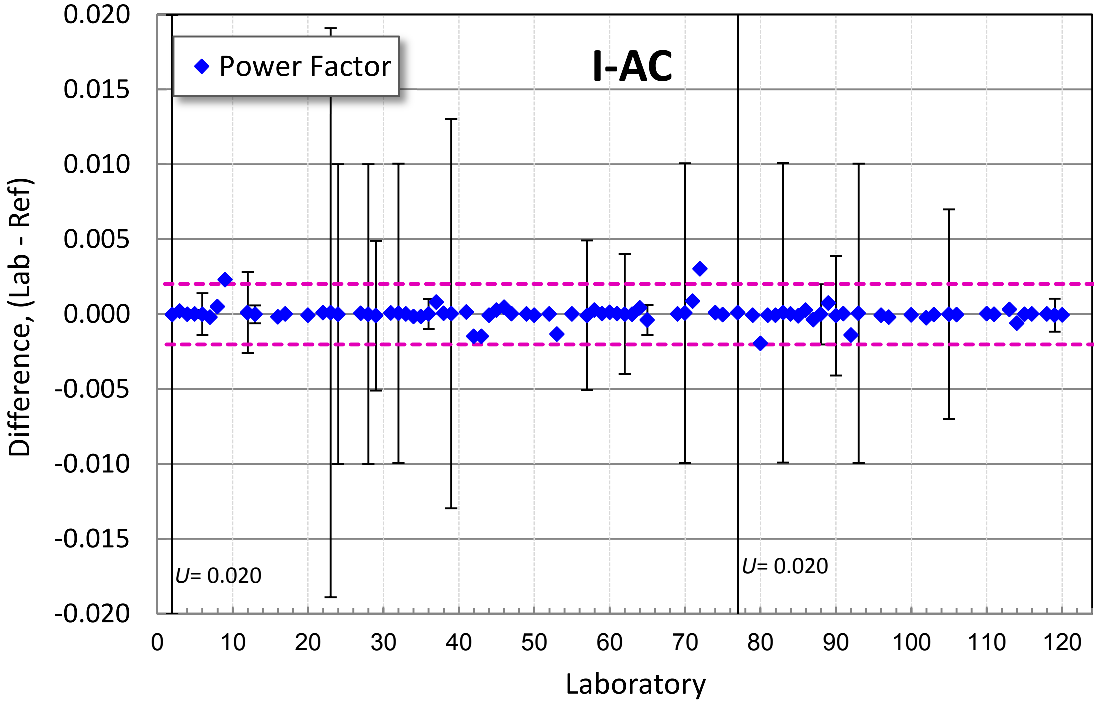

Figure 9-49. Differences of power factor for incandescent lamps AC operation (I-AC)

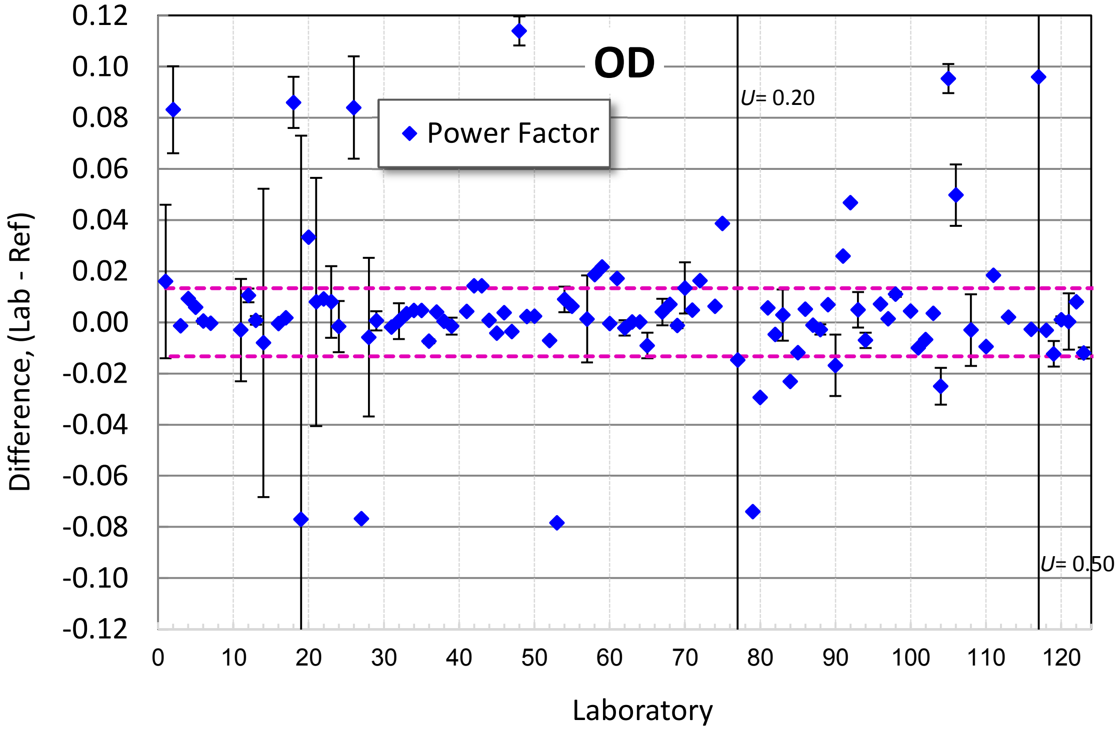

Figure 9-50. Differences of power factor for omnidirectional LED lamp (OD)

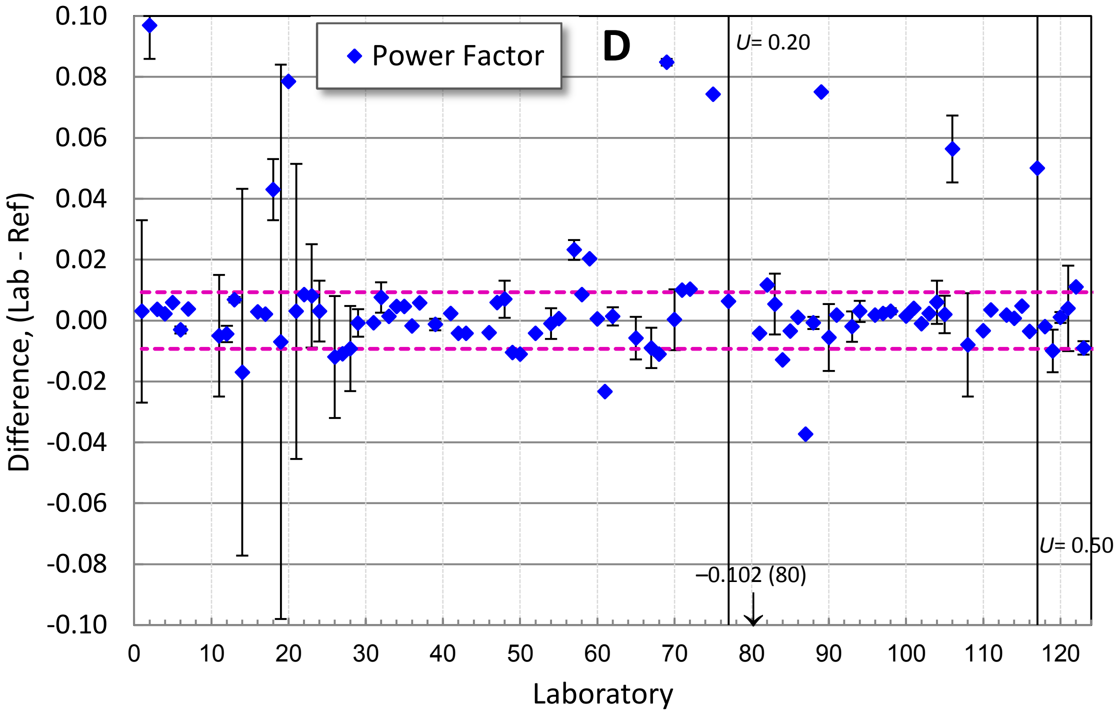

Figure 9-51. Differences of power factor for directional LED lamp (D)

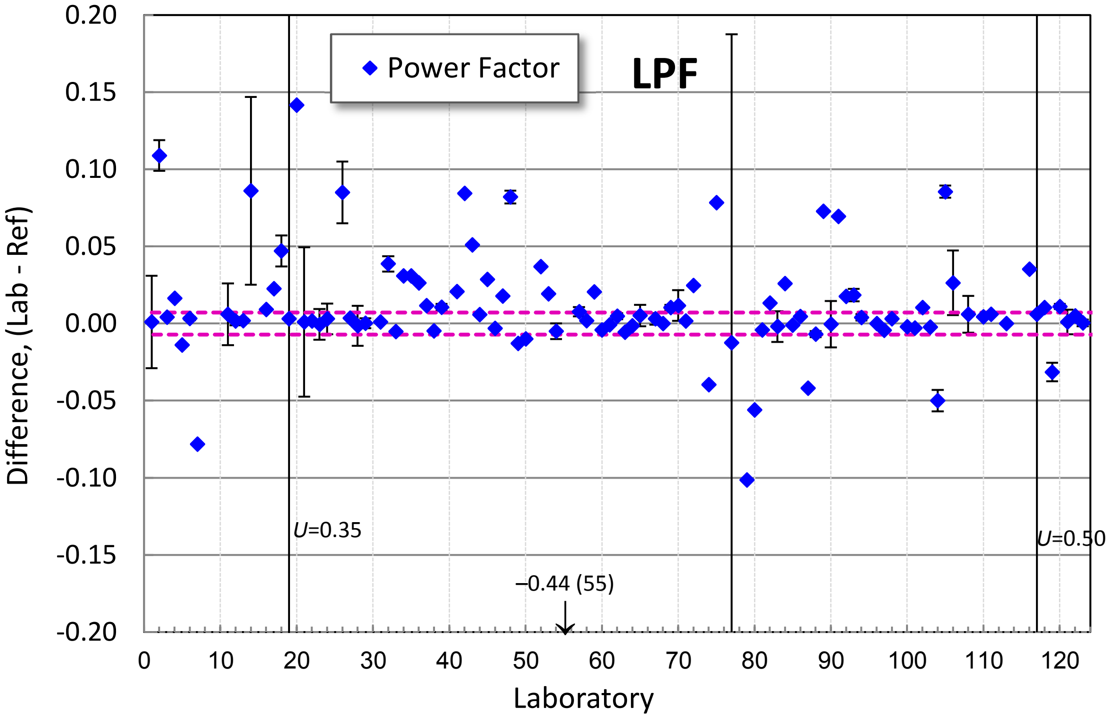

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Figure 9-52. Differences of power factor for low power factor lamp (LPF)

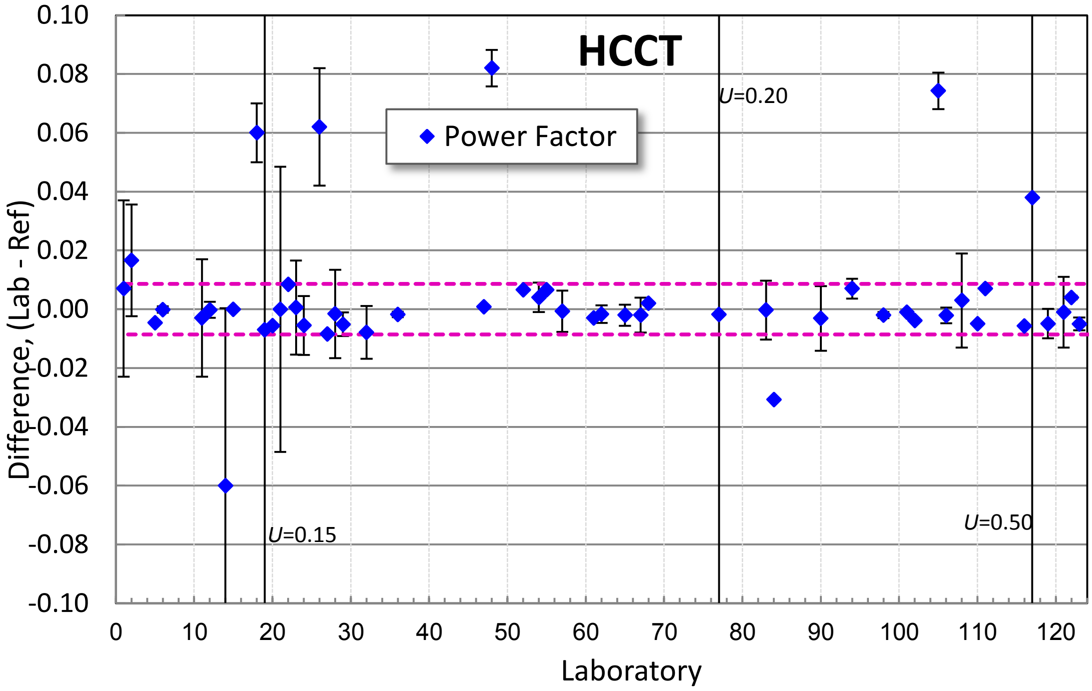


Figure 9-53. Differences of power factor for high CCT lamp (HCCT). Data of NIST-HCCT lamp (DC-operated) are not included.

Figure 9-54 shows comparison of the variations in the results for power factor for different artefact types, using robust standard deviation as described in Algorithm A, Annex C, ISO 13528:2005 [8]. Note that the power factor of I-AC (incandescent lamps) is 1, thus basically their differences are zero. Differences between LED lamps are observed, but these are due to the different electrical designs of the drivers operating these lamps, thus not related to intensity distribution or spectral power distribution. It is notable that the deviation of the LPF lamp is much larger than the others.

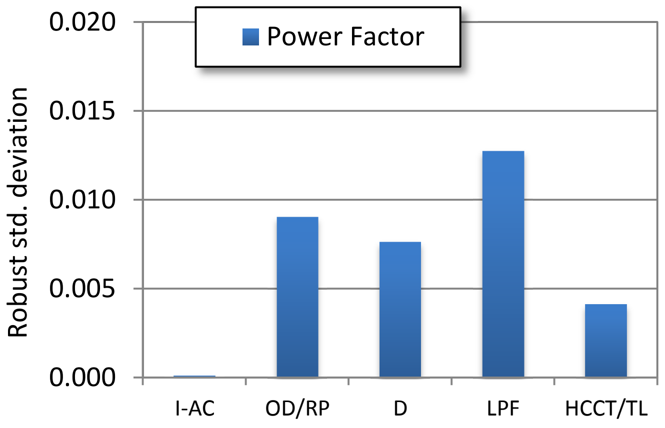


Figure 9-54. Summary of differences of power factor. The bars show the robust standard deviations of the differences of all laboratories for each type of lamp.

9.1.10 Comparison of sphere and goniophotometer

The results were sorted by the measurement system used, and photometric measurement results using integrating sphere systems and those using goniophotometers were compared. Some selected data are presented in Figures 9-55 to 9-57. Average values of all points of each instrument type (excluding one or two extreme points) are also shown in the graphs. The differences in these average values between the two instrument types are insignificant, and these data do not indicate systematic differences between the two instrument types. However, all three data points with a very large deviation in I-AC and OD were measured with goniophotometers.

Figure 9-57 for directional lamps measured with sphere systems shows more variation in the negative direction compared to the omnidirectional lamps (Figure 9-56). These larger variations for the directional lamps may be caused by errors that can occur when the sphere has poor spatial uniformity (e.g., dust or other contamination accumulated at the bottom of the sphere where the directional lamp projects the main portion of its light) , and when the integrating sphere system are calibrated with a standard lamp having dissimilar intensity distributions (in this case, an omni-directional standard lamp).

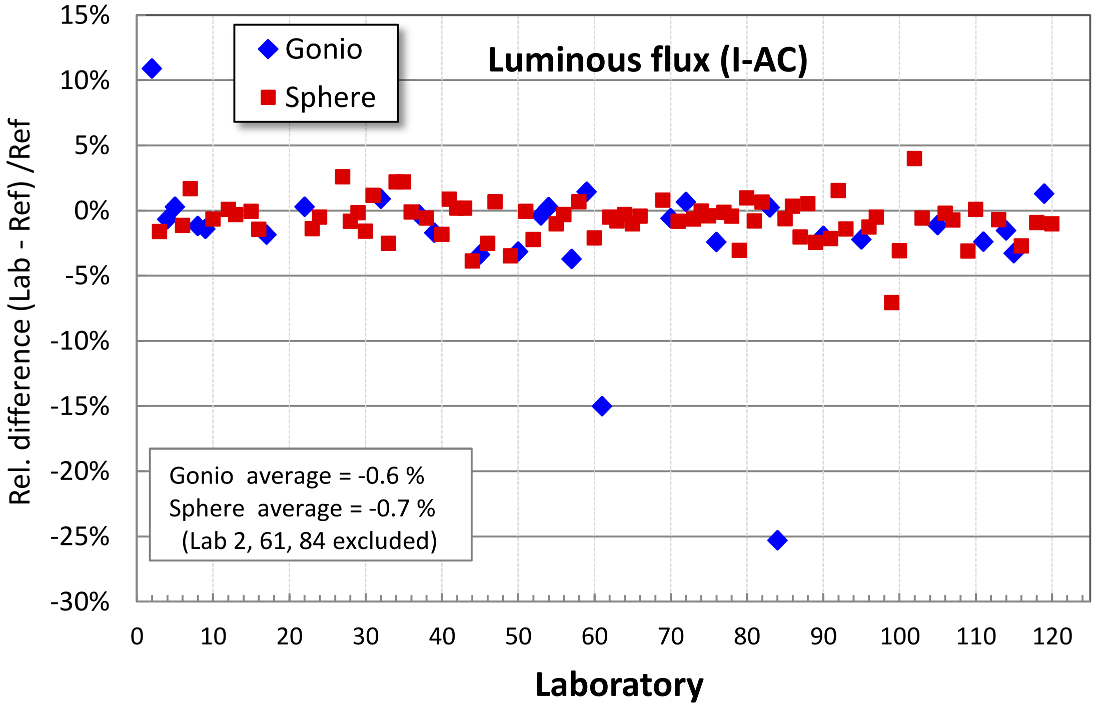


Figure 9-55. Comparison of integrating sphere and goniophotometer in luminous flux measurement for I-AC lamp.

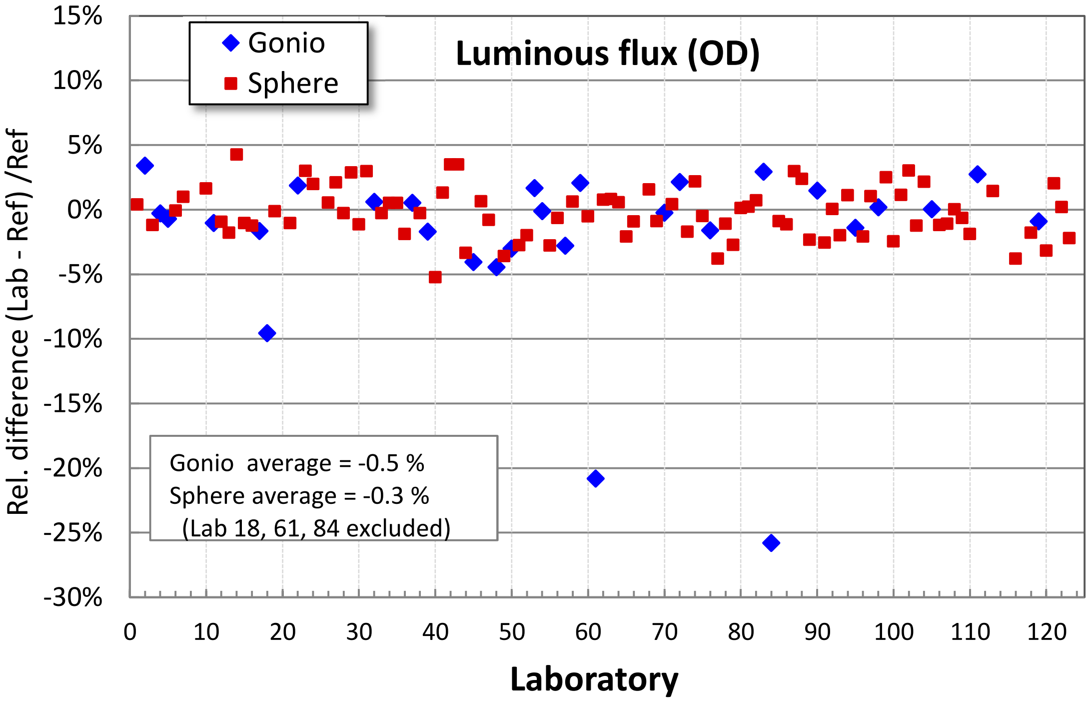


Figure 9-56. Comparison of integrating sphere and goniophotometer in luminous flux measurement for omnidirectinal LED lamp

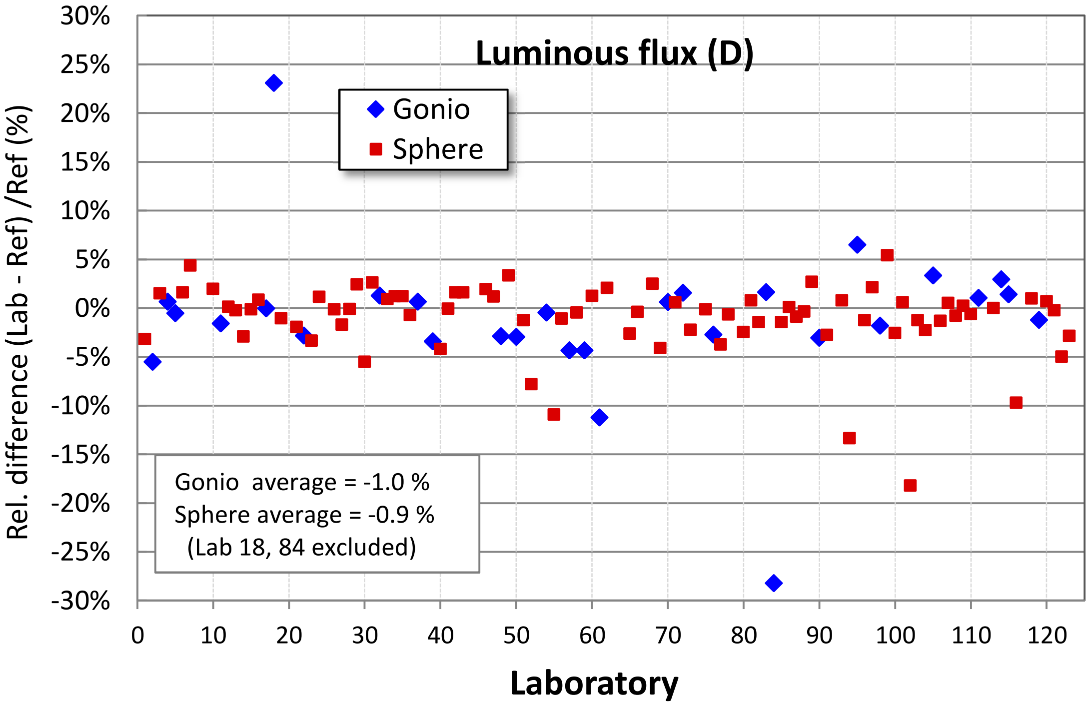


Figure 9-57. Comparison of integrating sphere and goniophotometer in luminous flux measurement for directional LED lamp.

9.1.11 Results of optional artefacts

In the results presented in Sections 9.1.1 to 9.1.9, the data for omnidirectional lamps (OD) included remote phosphor (RP) type lamps that are only used in one region, and the data of high CCT lamps (HCCT) included tubular lamp (TL) type, also only used in one region. These data were separated and shown in Figures 9-58 and 9-59, and the average values of luminous flux are also shown.

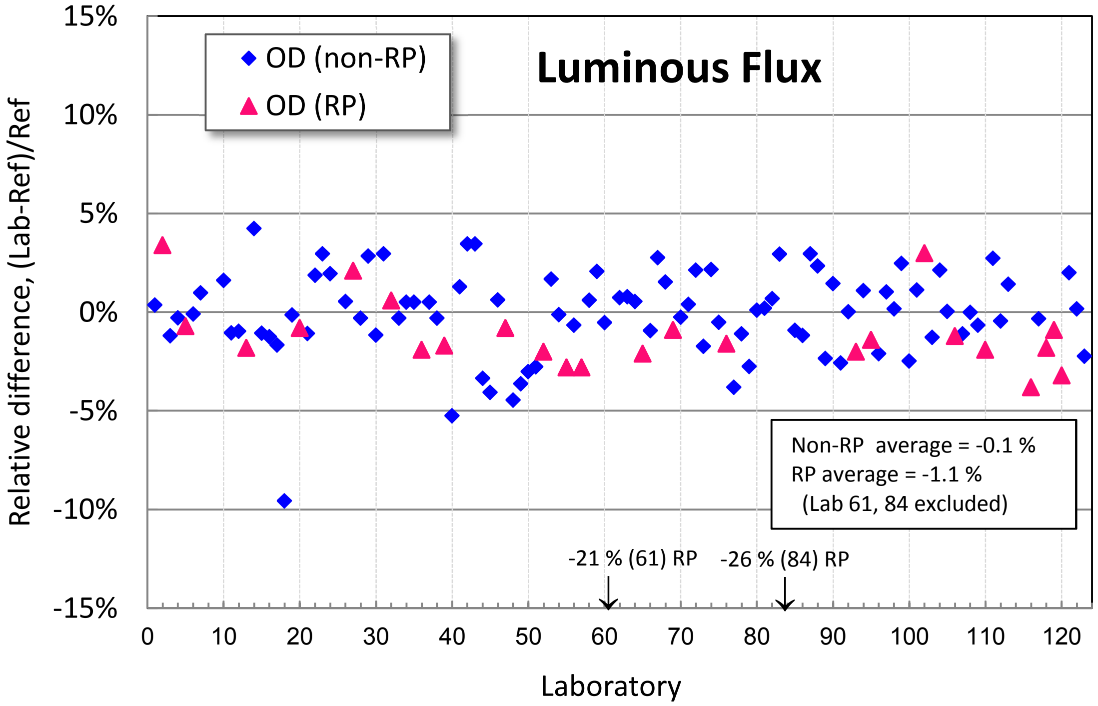


Figure 9-58. Comparison of remote phosphor OD lamp and other OD lamp in luminous flux measurement

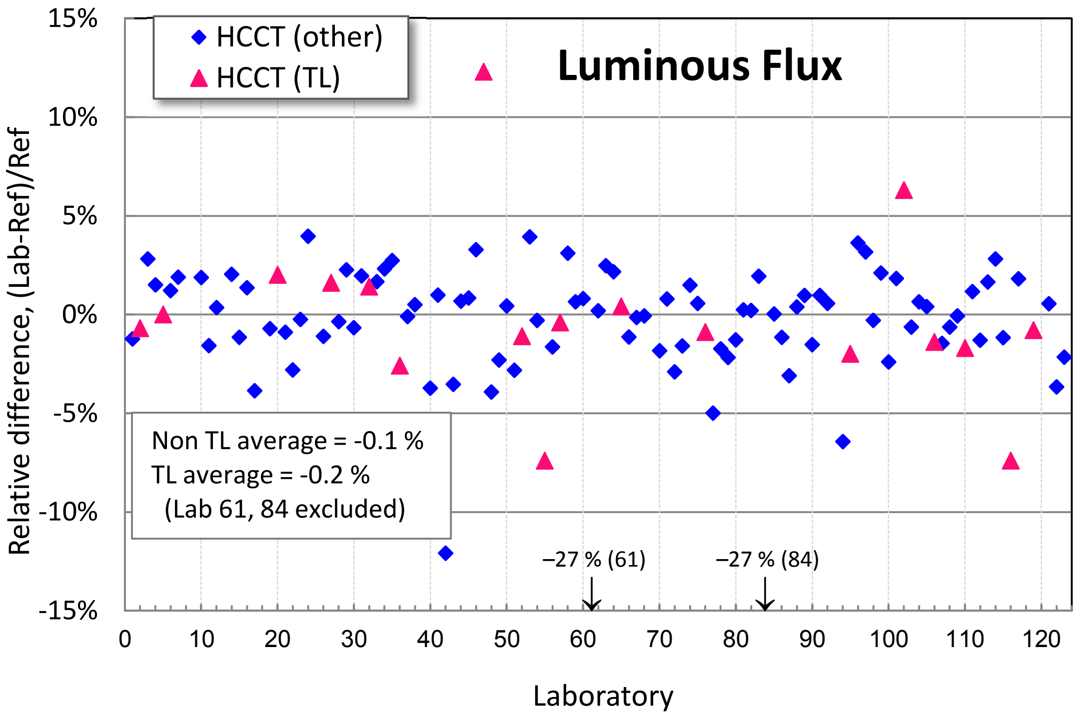


Figure 9-59. Comparison of tubular tyipe HCCT lamp and other HCCT lamp in luminous flux measurement

From Figure 9-58 and the average values of -0.1 % (non RP) and -1.1 % (RP), there seems to be some systematic difference between remote phosphor type and non-RP type. However, the RP and TL artefacts were only used by VSL, and these average values are from different groups of participants and different reference laboratories, thus other factors impacting the variability are also included. From Figure 9-59, there seems to be no systematic difference between the TL type and other LED lamps.

To investigate the remote phosphor lamp result further, the RP data are separated into data measured by goniophotometer systems and by sphere systems, as shown in Figure 9-60.

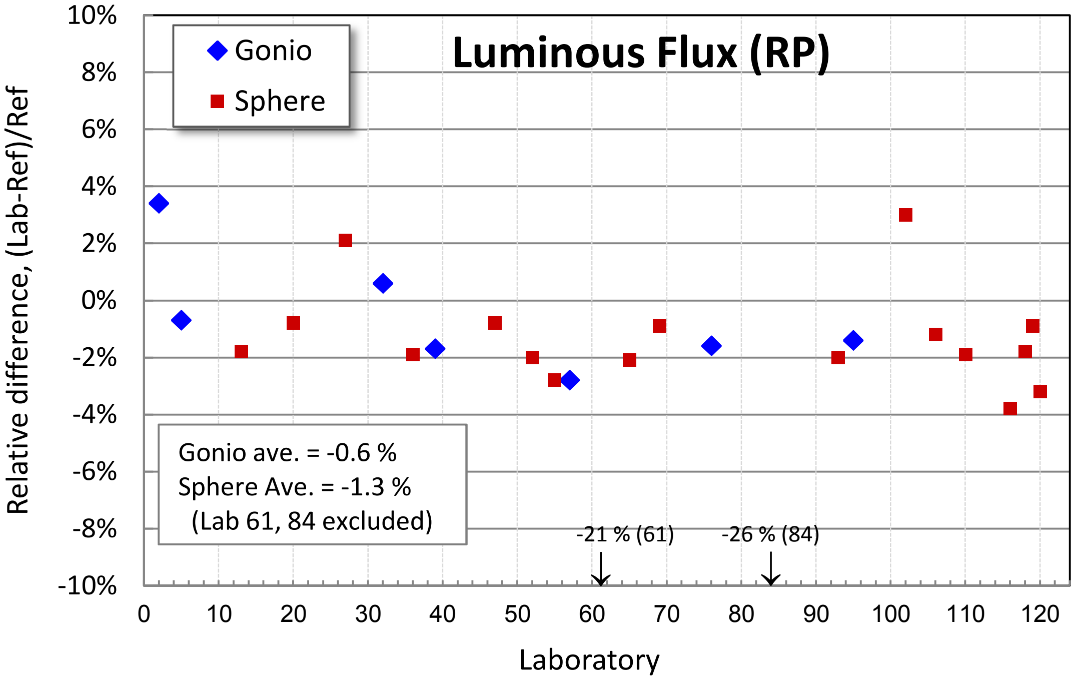


Figure 9-60. Comparison of goniophotometer systems and sphere systems in the measurement of luminous flux of remote phosphor lamps

The number of laboratories in this comparison is not large, and thus this observation is not conclusive, but a tendency can be seen in the data that the luminous flux of RP lamps with a sphere system (average -1.3 %) measured slightly lower than those measured with a goniophotometer system (-0.6 %). This requires further investigation, but one possible explanation would be that the large phosphor area of a remote phosphor lamp may be causing some error in self-absorption measurement in an integrating sphere due to fluorescence from the remote phosphor surface, which may affect the results in luminous flux.

Figure 9-61 shows a comparison of the luminous flux measurements of the I-DC (incandescent lamp operated on DC voltage) and I-AC (incandescent lamp operated on AC voltage). The luminous flux measurement data show an average value of ≈ –0.4 % for both, indicating no systematic difference between the two. Comparing current measurements, the standard deviation of AIST-IDC (100 V rated) was 0.34 % and that of I-AC (100 to 230 V rated) was 0.44 %. This indicates that I-AC (set by voltage) worked nearly as well as the DC operation of a similar incandescent lamp.

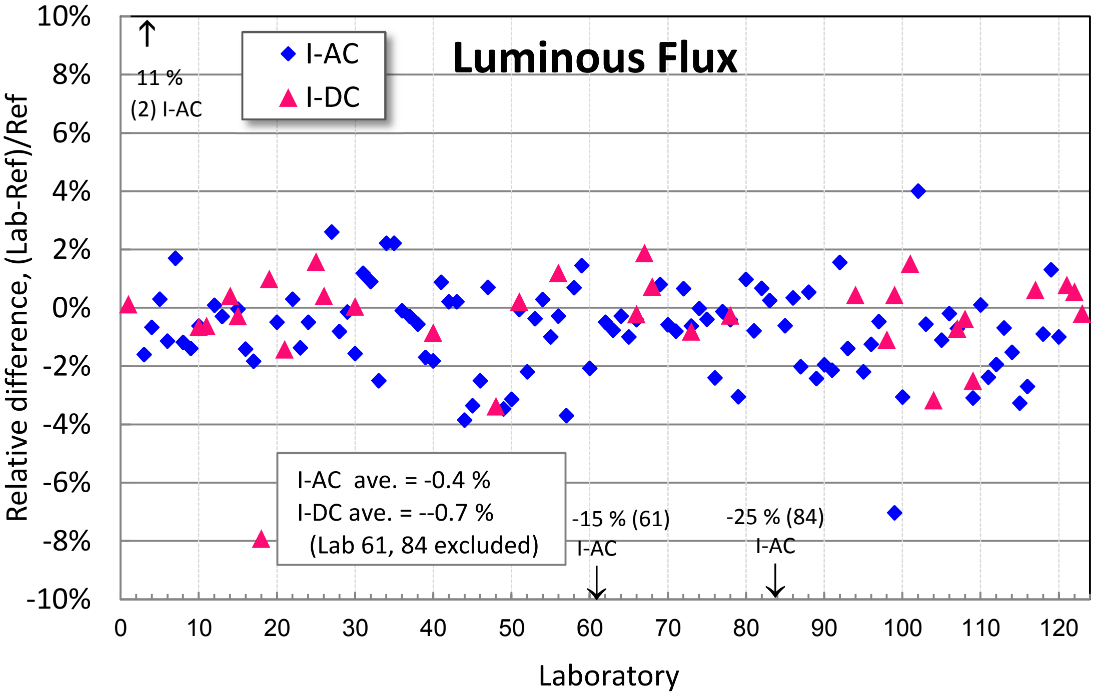


Figure 9-61. Comparison of I-AC and I-DC in luminous flux measurement

Comparing the incandescent lamp data set by current (NLTC-IDC used in APLAC PT, 12 V rated) and lamp set by voltage I-AC (100 to 230 V rated), the variations in luminous flux were similar, both having a standard deviation of ≈ 0.4 %. However, the standard deviation of voltage of NLTC-IDC was 5.6 %, which is one order of magnitude larger than that of current of I-AC (100 to 230 V rated), which was 0.44 %. This large variation in voltage was possibly caused by a voltage drop due to the contact resistance between the lamp base and the lamp socket, especially because this was a low voltage lamp (≈ 11 V) with a high current (≈ 4 A). However, the data showed this is only an issue for measured voltage and does not affect luminous flux and other quantities of a lamp as long as the current measurement is accurate. This, in turn, suggests that the variation in luminous flux and other quantities would be very large if voltage were used as the set parameter for such a low-voltage lamp.

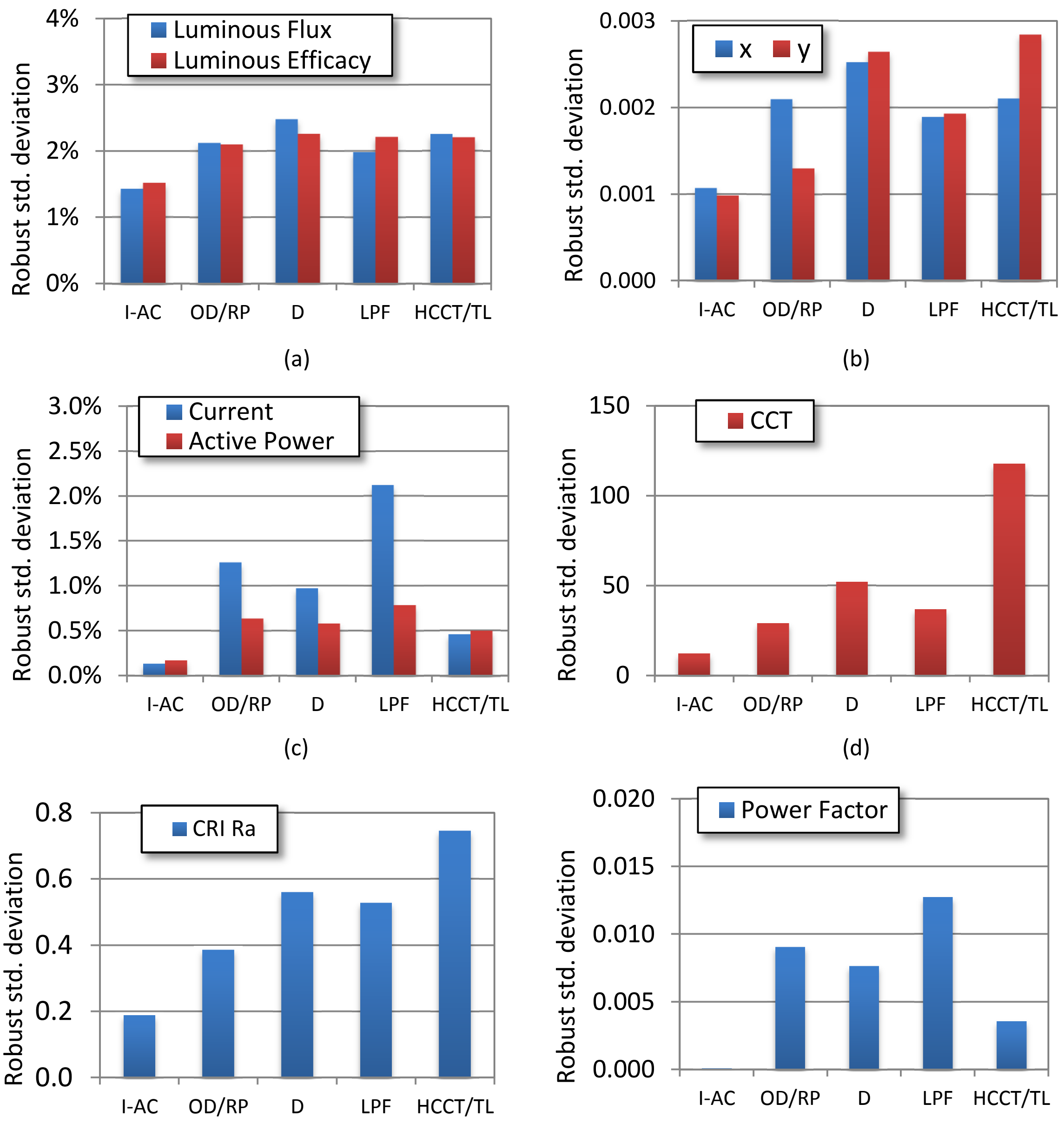
9.1.12 Discussions of the results of differences

The differences observed for total luminous flux and luminous efficacy are consistent with the data presented in Sections 9.1.1 and 9.1.2, and most laboratories agree within ± 4 % (OD) to ± 5 % (D, LPF, HCCT), which is at an expected level. However, there are a few laboratories which were found to have very large deviations (up to 30 %) in each artefact type.

The differences for chromaticity *x* and *y* (presented in Sections 9.1.5 and 9.1.6) are similar for all LED artefacts, and most laboratories agree within ± 0.005 for all artefact types, which is at the expected level. However, there are also some extremely large deviations up to 0.2 in *x* and 0.08 in *y*.

The measurement variations in RMS current turned out to be much larger than expected, and the reported uncertainties were significantly underestimated. It is evident that there are some additional uncertainty components that were overlooked. The large variations may have been caused by differences in the characteristics of the AC power meter (bandwidth, etc.) and/or the AC power supplies (output impedance, bandwidth, etc.) used, and it is difficult to identify the variation unless different meters or power supplies are compared. These electrical issues with LED lighting products have been identified and discussed elsewhere in the literature (for example, “Influence of Current and Voltage Harmonic Distortion on the Power Measurements of LED Lamps and Luminaires” [10]), but solutions have not been found. For now, some additional uncertainty for RMS current and power factor measurements should be considered by laboratories when evaluating their uncertainty budgets.

To summarize and compare the results of all artefact types, *robust standard deviations* of all the results as reported in Sections 9.1.1. to 9.1.9 are calculated and shown together in Figure 9-62 (a)-(f).

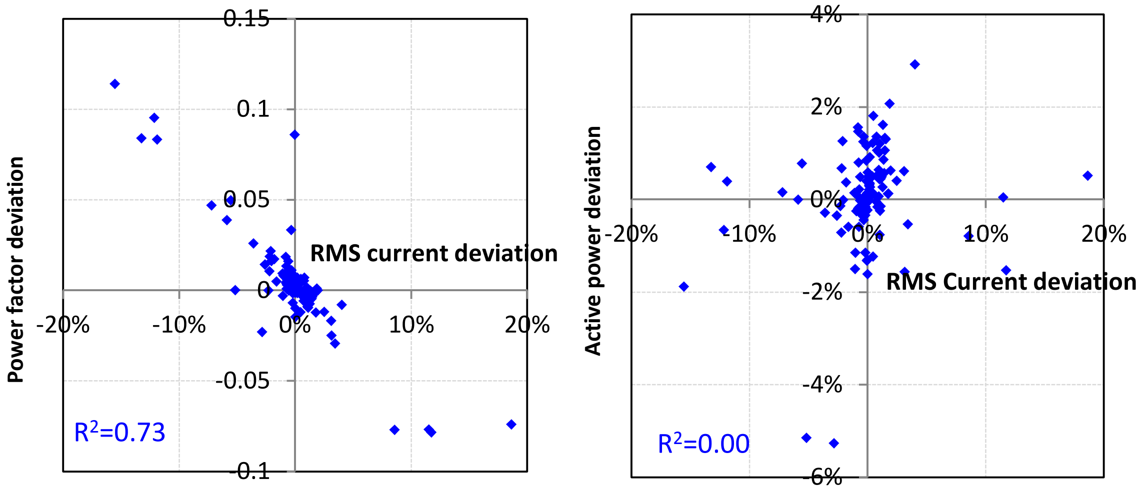


(a) (b) (c) (d) (e) (f)

Figure 9-62. Summary of differences for all quantities and all artefact types; the robust standard deviations in Figures 9-6, 9-12, 9-18, 9-24, 9-30, 9-36, 9-42, 9-48, and 9-54 shown together

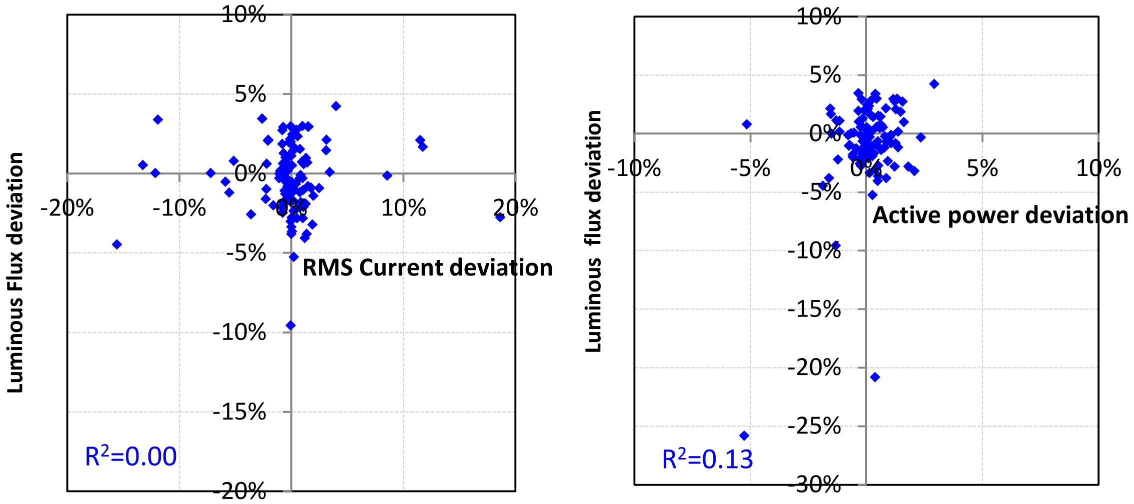
Figure 9-62 (a) shows that the variations in measured luminous flux and luminous efficacy for LED lamps (OD, D, LPF, HCCT) are about 1.5 times larger on average than those for incandescent lamps (I-AC). Figure 9-62 (b) shows that the variations in measured chromaticity *x, y* for LED lamps are about two times larger than those for incandescent lamps. These results verify that there are significant uncertainty components specific to LED lamps, which increase the uncertainties of photometric and colorimetric quantities.

The variations in RMS current for all LED lamps, as discussed above, are very large as verified in Figure 9-62 (c), with variations on average nearly ten times greater than those for incandescent lamps. The variation for the lower power factor (LPF) lamp is especially large. Some extreme results were found showing deviations up to 38 % in the LPF lamp. These large measurement deviations may be caused by different characteristics of the AC power supply interacting with large distortions in the LED lamp current waveforms with very high frequency components. The variations in active power, shown in Figure 9-62 (c), however are not as large as the RMS current variations. The variations in luminous flux, Figure 9-62 (a), show nearly no difference between the LED lamp types. And despite the very large variations in RMS current measurements for the LPF lamp, the variations in the luminous flux and chromaticity measurements on those same lamps are no larger than on other lamp types. This implies that the variation in RMS current is not affecting the luminous flux measurements. The variations in power factor, Figure 9-62 (f), shows the same tendency as RMS current, and thus it seems these measurands are correlated. To investigate this further, correlations between the variations in RMS current and power factor, luminous flux, or other combinations, were evaluated, and the results for OD lamp are shown in Figure 9-63.



(a) RMS current and power factor

(b) RMS current and active power



(c) RMS current and luminous flux

(d) Active power and luminous flux

Figure 9-63. Correlations between the deviations of two quantities for OD lamp.

Figure 9-63(a) shows a strong correlation between RMS current and power factor, and other figures show that there is almost no correlation between RMS current and active power or luminous flux. The correlation between RMS current and power factor is in the direction to cancel the variation in active power. This explains why large deviations in RMS current did not affect other measured quantities significantly. The analyses of other LED lamp types showed similar results to these findings for the OD lamp.

The variations in power factor for LED lamps were also larger than expected. The deviations were largely within ± 0.02 (OD, D, HCCT) to ± 0.1 (LPF) with one laboratory having an extremely large deviation of 0.44.

The variations in CCT, in Figure 9-62(d), and CRI R_a, in Figure 9-62 (e), for LED lamps are also much larger than those for incandescent lamps (i.e., the largest difference of CCT for HCCT lamp is primarily due to the nonlinearity of the CCT scale). These measurement errors are caused in spectroradiometers that are measuring spectral distributions which are dissimilar to the calibration source, an incandescent lamp. The variation in CRI R_a is highest for the HCCT lamps; and this finding can be explained by the fact that HCCT lamps have a spectral distribution pattern that is the most dissimilar to the incandescent lamps of the different LED artefacts tested. This difference is primarily due to the high blue peak in the spectral distribution function of the LED (i.e., blue die with an amber phosphor).

The comparison between the sphere system and goniophotometer, shown in Figures 9-55 to 9-57, implies that there might be a higher risk of mistakes in the absolute measurement of total luminous flux with goniophotometers (e.g.., spatial integration calculations), compared to integrating sphere systems where measurements are in direct comparison with standard lamps and very large errors may be less likely. However, Figure 9-57 showed large variations in the integrating sphere results in a negative direction, which may be caused by measuring directional lamps in a sphere that had most likely been calibrated with an omnidirectional lamp, and with poor spatial uniformity of the sphere.

9.2 Uncertainties reported

Figures 9-64 to 9-72 show the uncertainties (*k*=2) of measurements of I-AC and OD lamps for all measurement quantities reported by the participating laboratories. For power factor, OD and LPF (instead of I-AC) are presented instead of I-AC and OD. The lab numbers 1 to 123 on the horizontal axes are the laboratory numbers of the participants, and 125 to 128 are Nucleus laboratories. The uncertainties of other LED lamps are similar to those of OD. Most of OD lamps used had CCT of 2700 K to 3000 K. Note that not all laboratories reported uncertainties (e.g., data from NVLAP/NIST PT-linked laboratories did not include uncertainties.) Section 9.2.1 discusses these results.

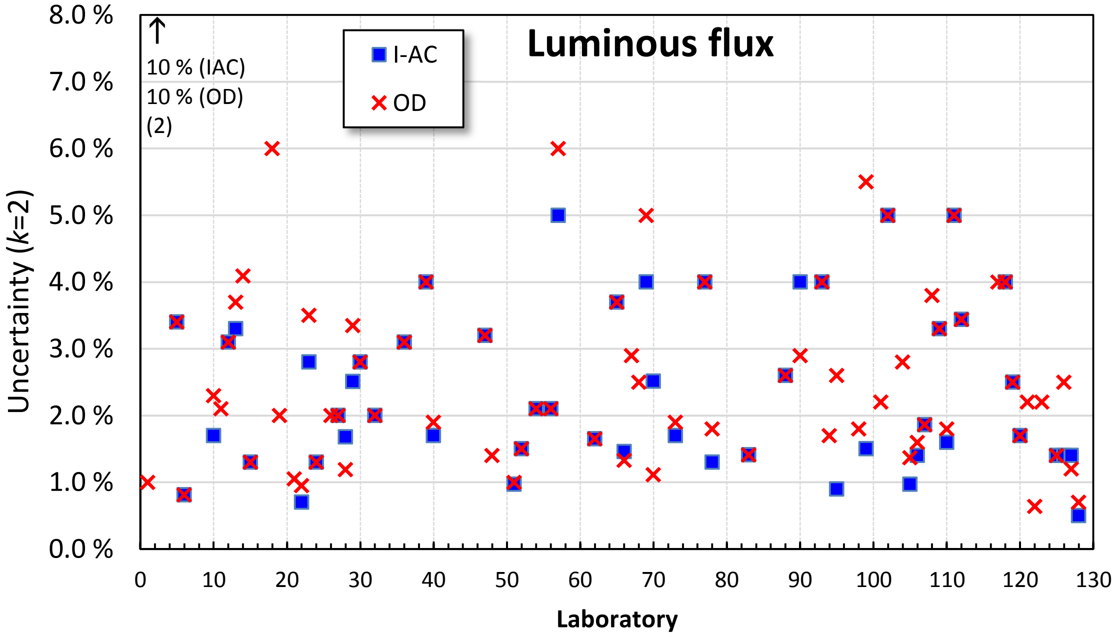


Figure 9-64. Uncertainties (k=2) of luminous flux reported by the laboratories

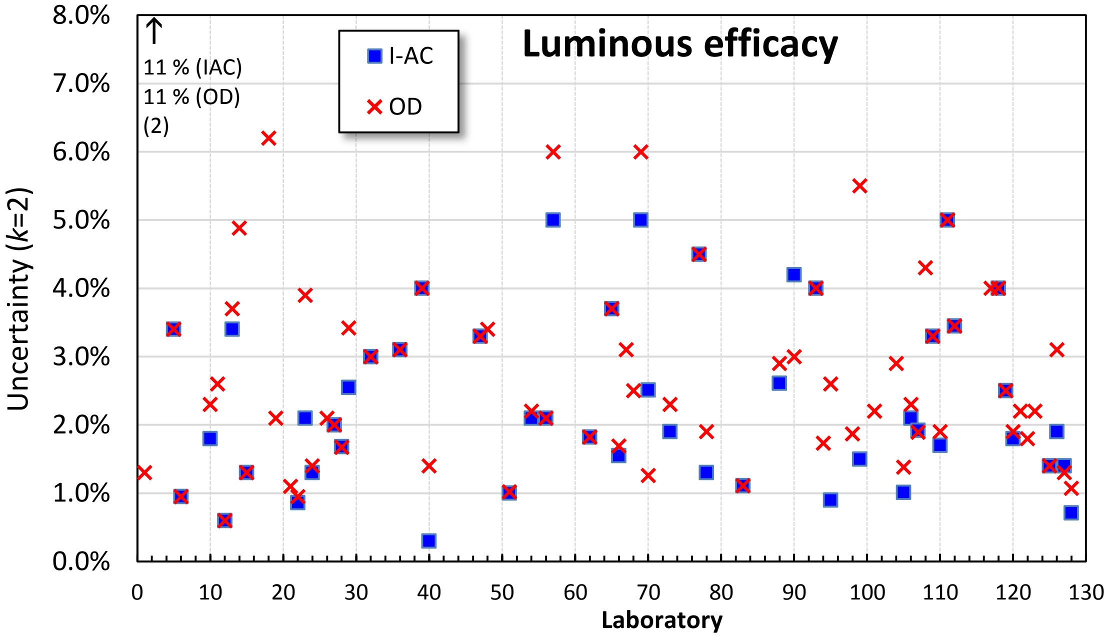


Figure 9-65. Uncertainties (k=2) of luminous efficacy reported by the laboratories

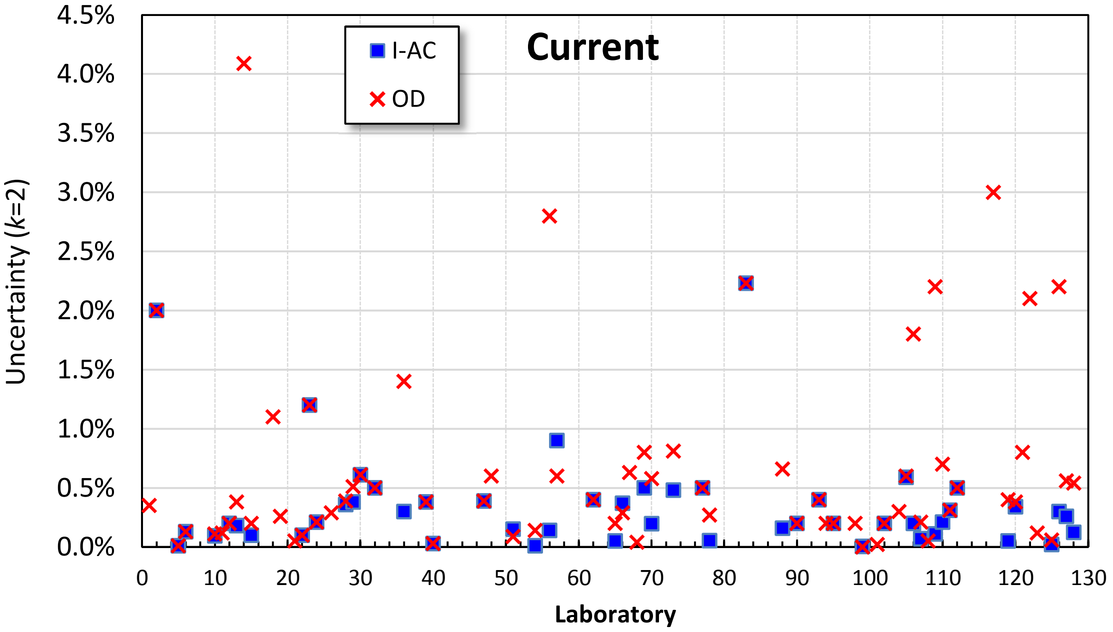


Figure 9-66. Uncertainties (k=2) of RMS current reported by the laboratories

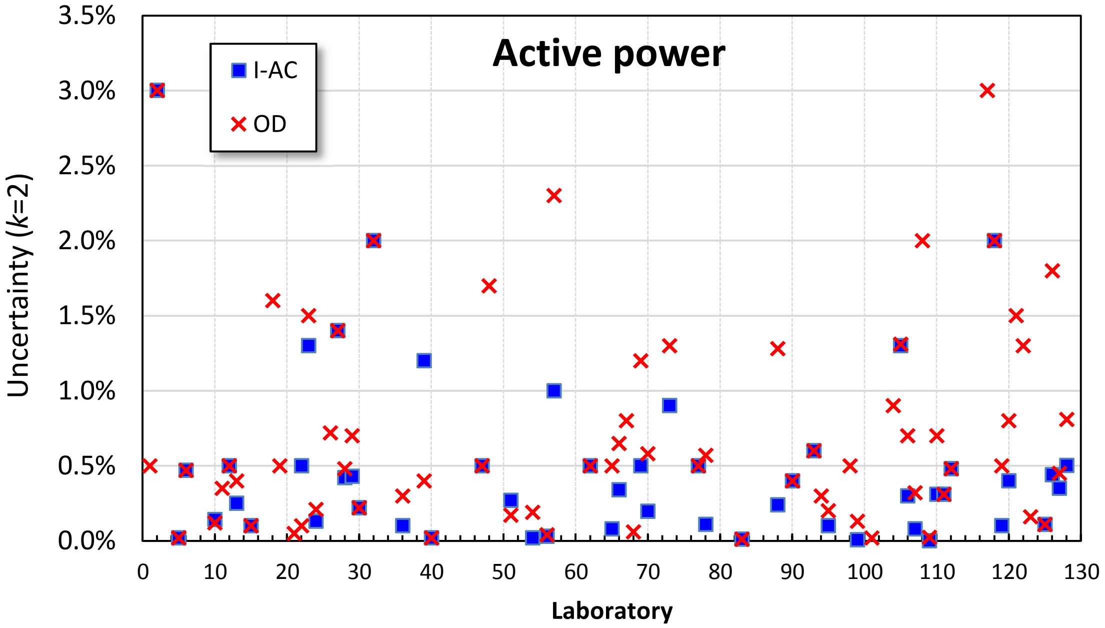


Figure 9-67. Uncertainties (k=2) of active power reported by the laboratories

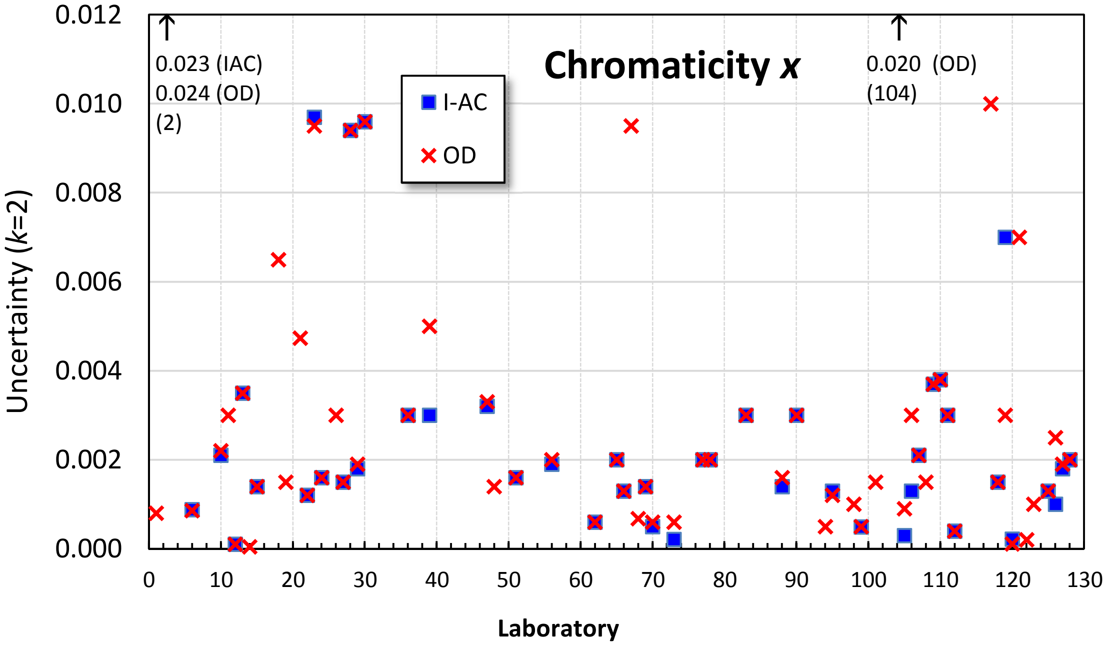


Figure 9-68. Uncertainties (k=2) of chromaticity x reported by the laboratories

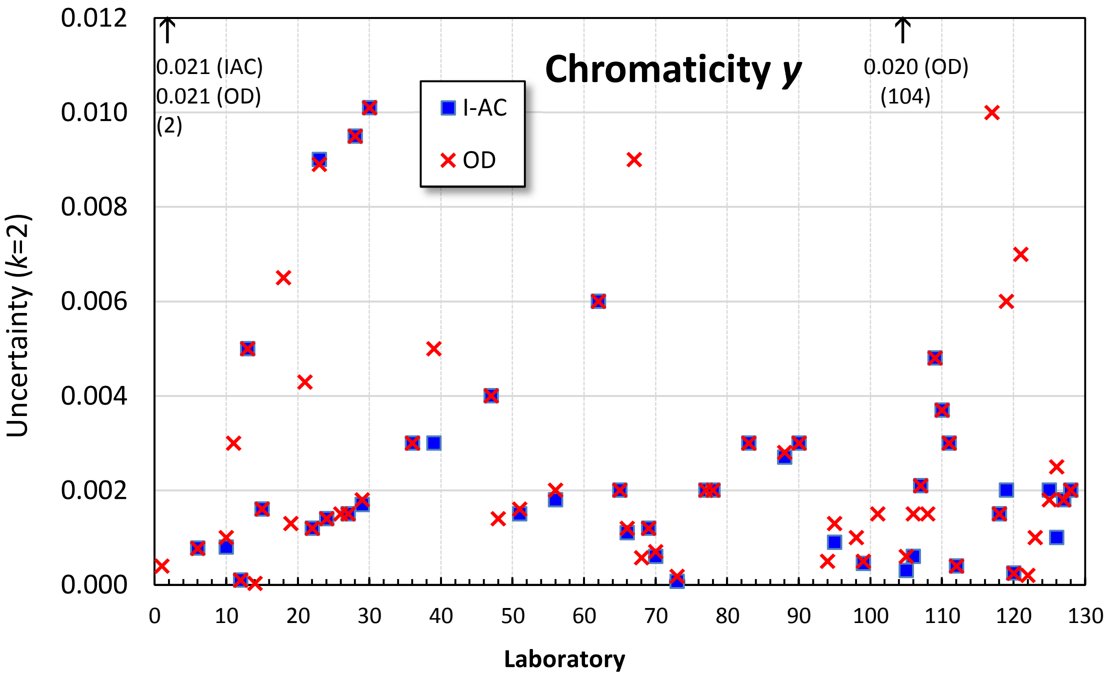


Figure 9-69. Uncertainties (k=2) of chromaticity y reported by the laboratories

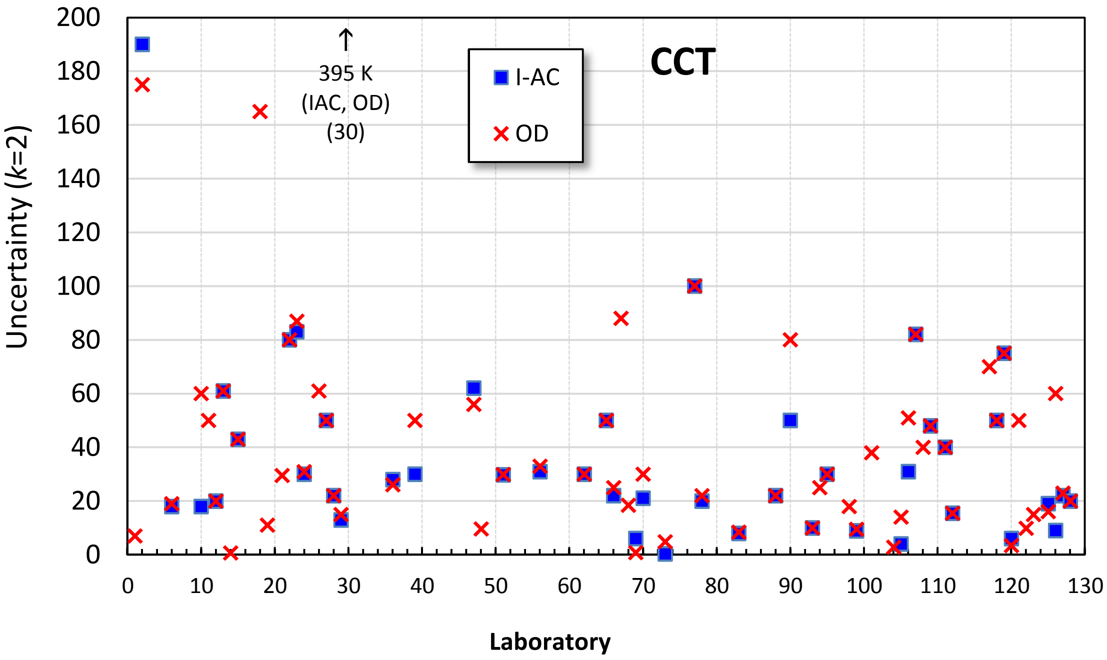


Figure 9-70. Uncertainties (k=2) of CCT reported by the laboratories. CCT of most of the OD lamps were 2700K to 3200K

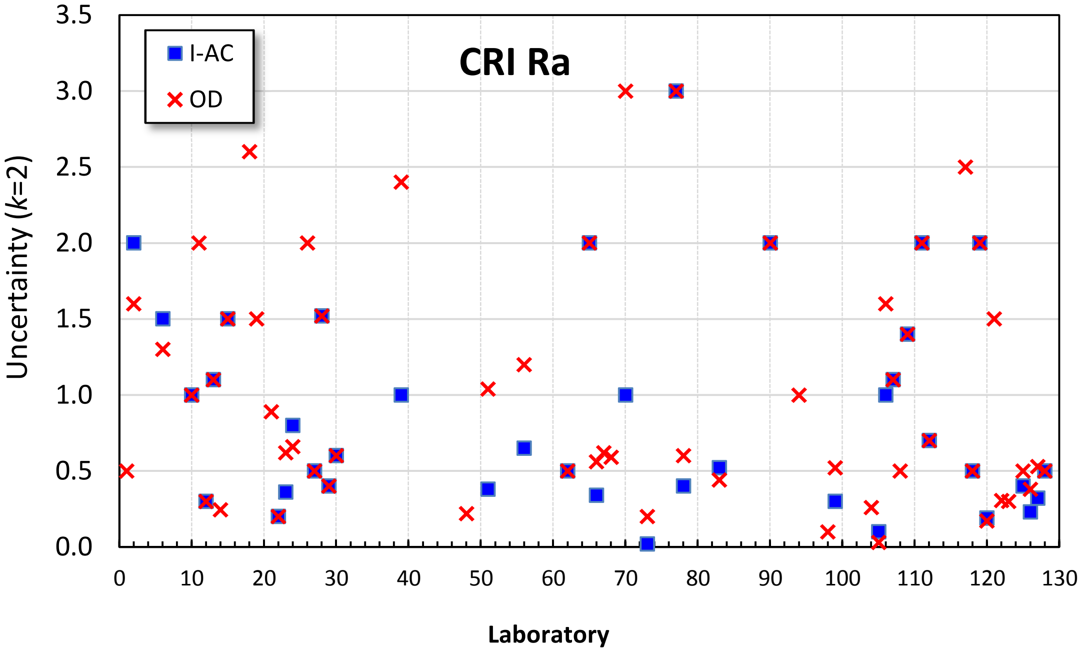


Figure 9-71. Uncertainties (k=2) of CRI R_a reported by the laboratories.

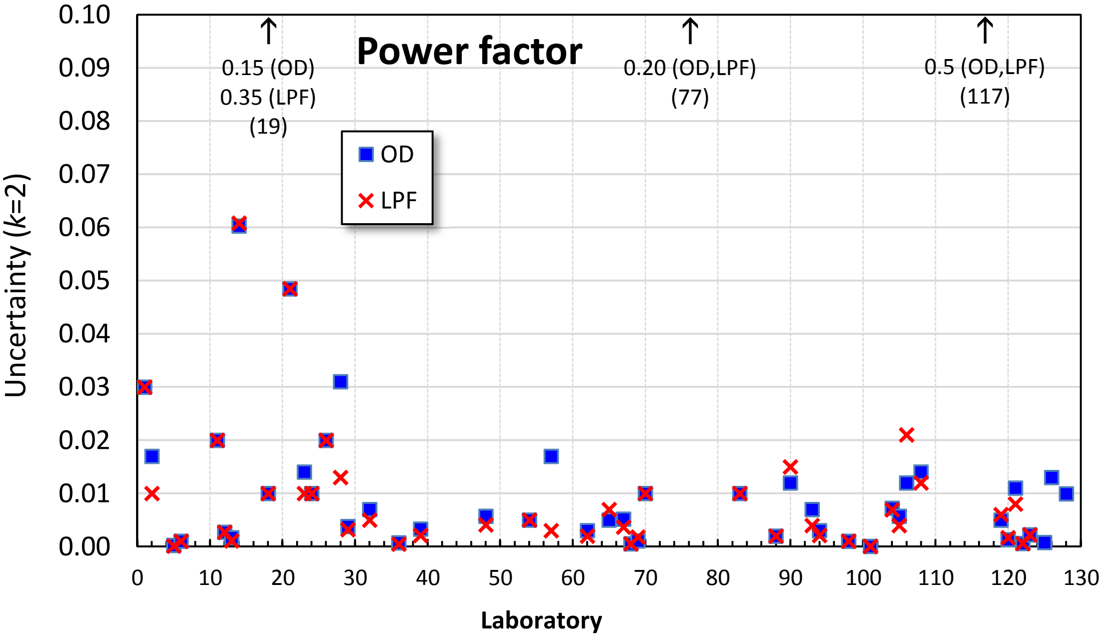


Figure 9-72. Uncertainties (k=2) of power factor reported by the laboratories.

9.2.1 Discussion

In all results presented in section 9.2 above, the uncertainty values reported by the participants had a very large range, and the reported uncertainties in many cases were unreasonably small, and in some cases, unreasonably large.

For luminous flux, Figure 9-64, the reported uncertainties (*k*=2) ranged mostly from about 1 % to 6 % and up to 10 %. While there are many cases of underestimated uncertainties, this range (one order of magnitude) is not as large as that for other quantifies. From observations of results for luminous flux given in section 9.1.1 (comparing the uncertainty bars and deviations of the assigned values), the range of the reported uncertainties for luminous flux are not as problematic as that for other quantities.

The reported uncertainties (*k*=2) of chromaticity *x*, Figure 9-68, and y, Figure 9-69, had a very large range, from 0.0001 to 0.02. More than ten laboratories reported uncertainties for LED lamps less than 0.001, and a few of them reported 0.0001 or 0.0002 in *x* and *y*, which could be only repeatability of the instruments. This implies that some participants do not understand the uncertainties for these colour quantities. Also, several laboratories did not report uncertainties for colour quantities while they reported uncertainties for photometric and electrical quantities. This indicates that many laboratories are experiencing difficulties in their uncertainty evaluations for colour quantities.

The reported uncertainties for RMS current, Figure 9-66, also had a large range, from 0.01 % to 4 %. The results in Section 9.1.3 showed an unexpectedly large difference in the current measurements for LED lamps, and these reported uncertainties for LED lamp currents were significantly underestimated in many cases.

The reported uncertainties of active power, Figure 9-67, also had a large range, from 0.02 % to 4 %, however the active power uncertainties were underestimated to a lesser degree than were the current uncertainties.

For power factor, Figure 9-72, the range of reported uncertainties was from 0.001 to 0.5, an extremely large range. Several laboratories reported uncertainties of 0.003 or less while the deviations of results were much larger (standard deviation ≈ 0.01 for LED lamps).

9.3 z’ scores

The z’ scores were calculated for all the results (all quantities, all artefacts, and all participants) and reported in the Participants Results Reports that were issued to each participant, and also all graphic data were presented in the Regional Interim Reports issued by each Nucleus Laboratory to the participants. In the following sections, the z’ scores of two artefact types (I-AC and LPF) for all quantities are presented. These two lamp types were selected because they represent the least problematic (I-AC) and most problematic (LPF) examples in many cases. The dashed lines in each figure show z’= ± 3, outside of which the results are generally judged unsatisfactory.

9.3.1 I-AC lamp

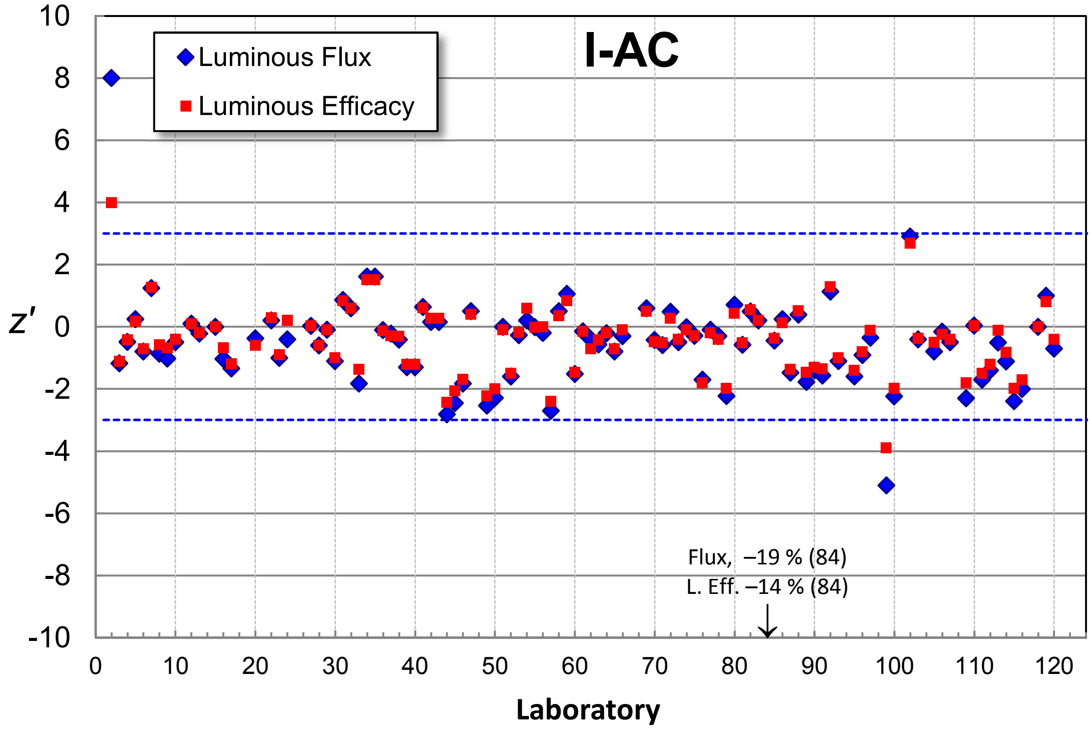


Figure 9-73.. z' scores for total luminous flux and luminous efficacy for I-AC

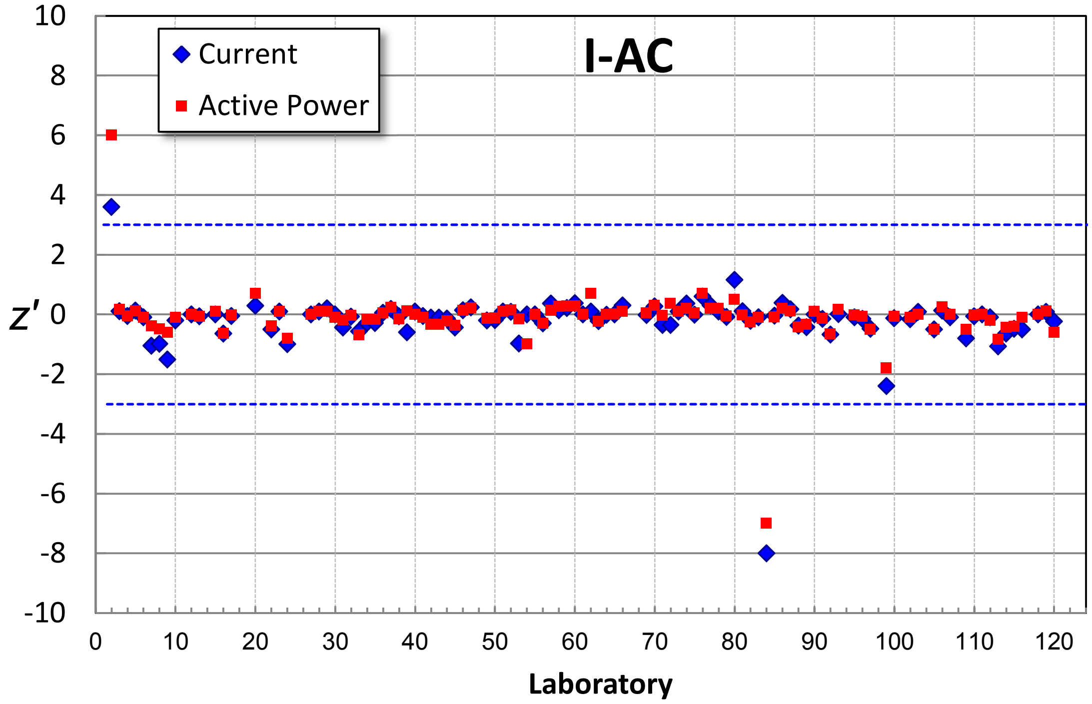


Figure 9-74. z' scores for RMS current and active power for I-AC

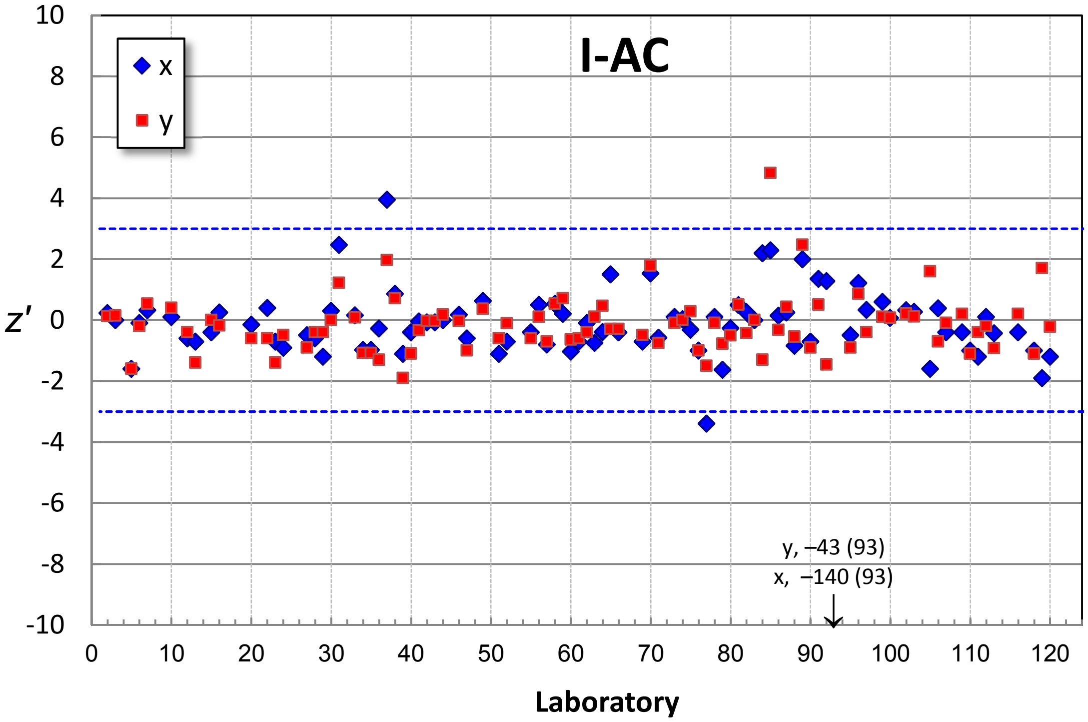


Figure 9-75. z' scores for chromaticity x, y for I-AC

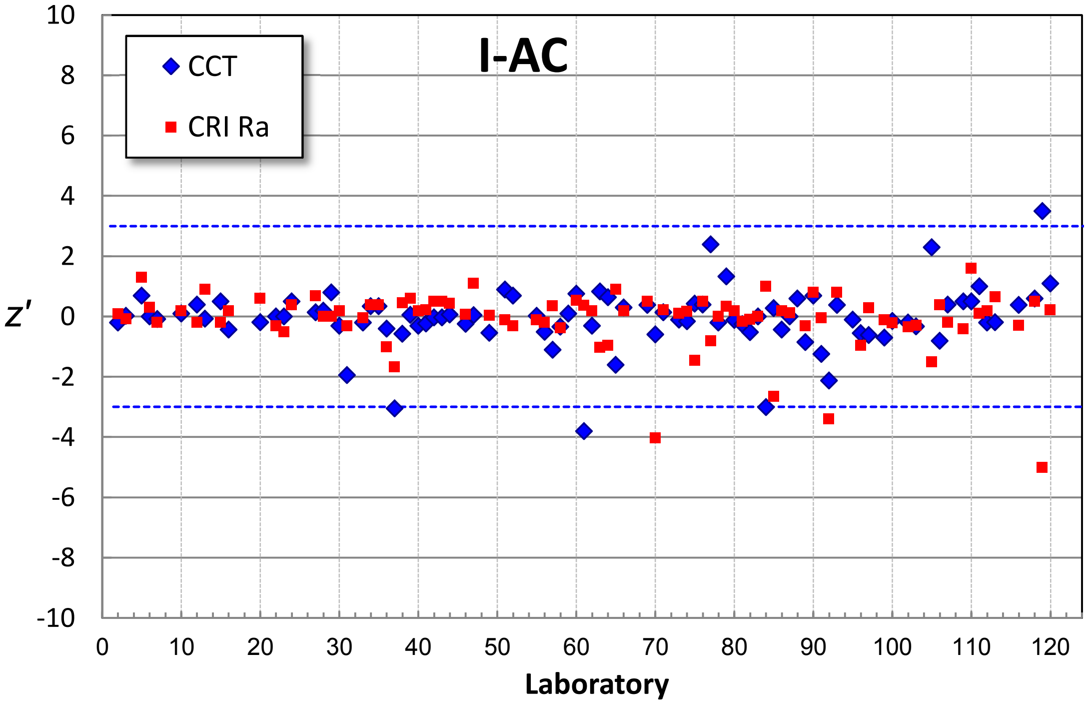


Figure 9-76. z' scores for CCT and CRI R_a for I-AC

9.3.2 LPF lamps

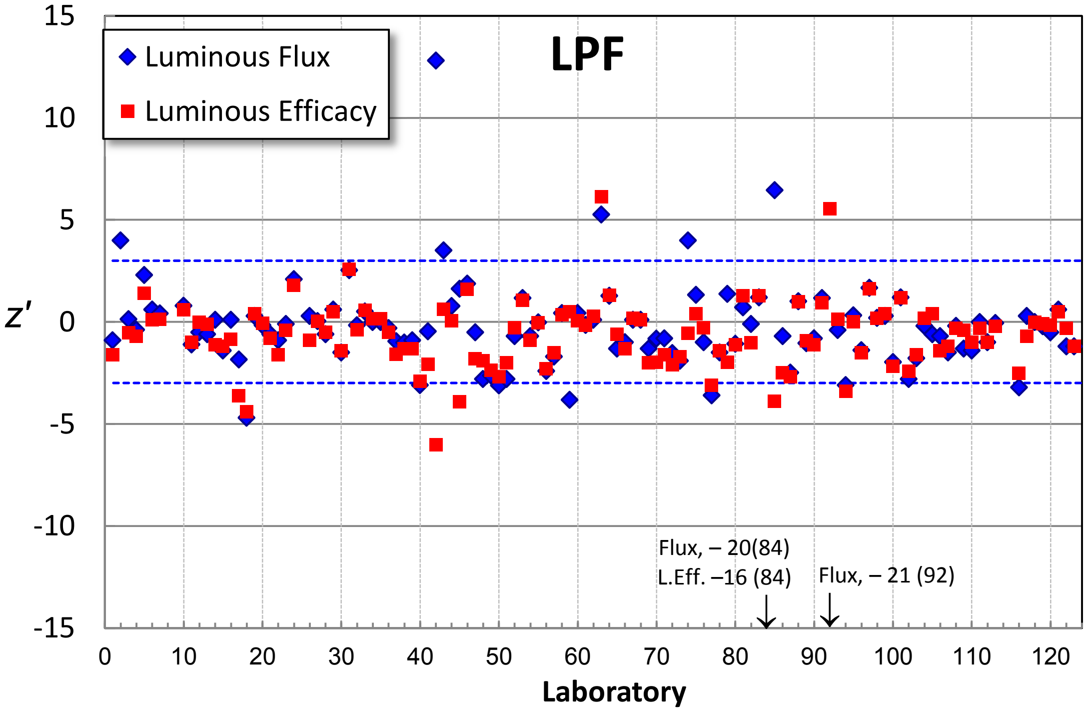


Figure 9-77. z' scores for total luminous flux and luminous efficacy for LPF

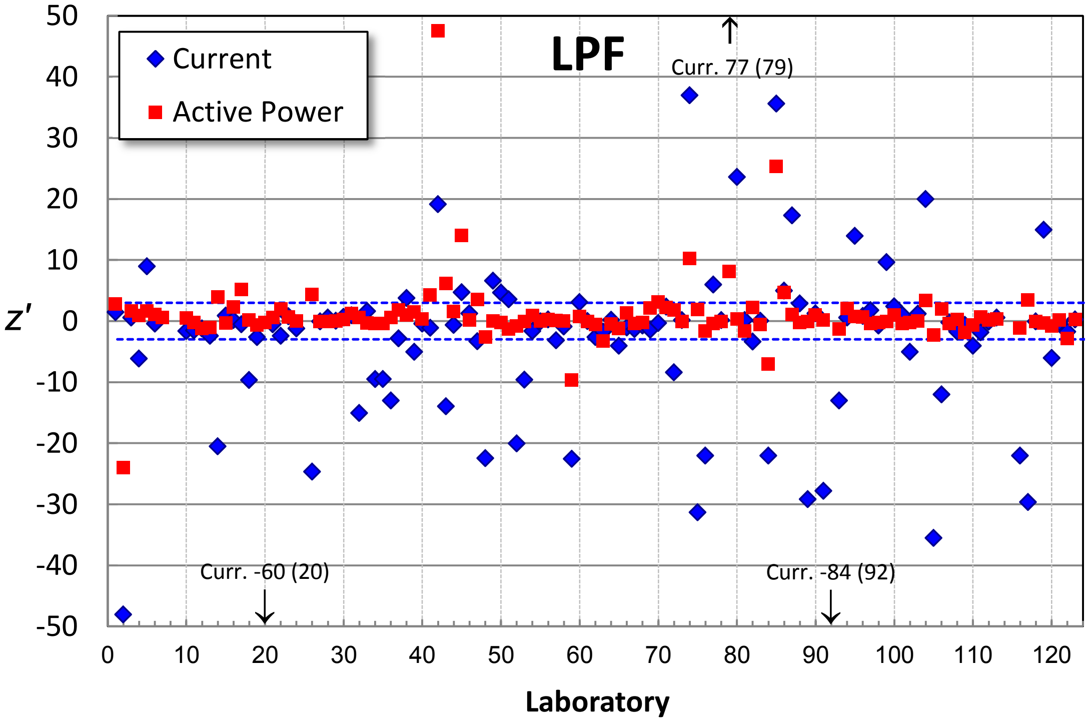


Figure 9-78. z' scores for RMS current and active power for LPF

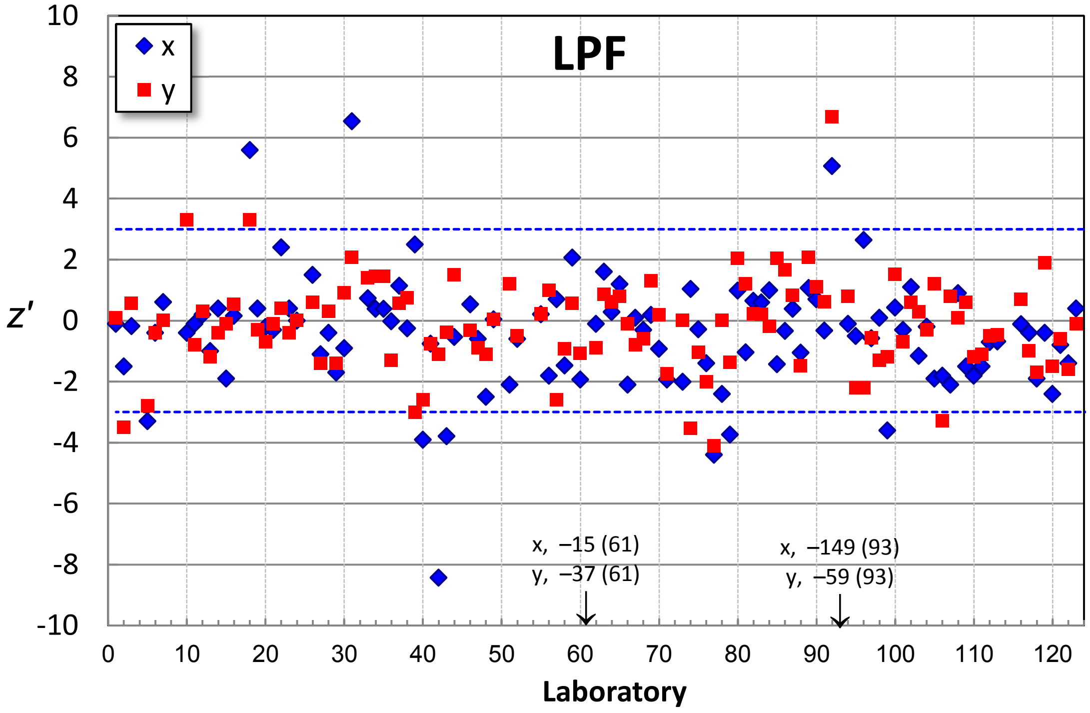


Figure 9-79. z' scores for chromaticity x, y for LPF

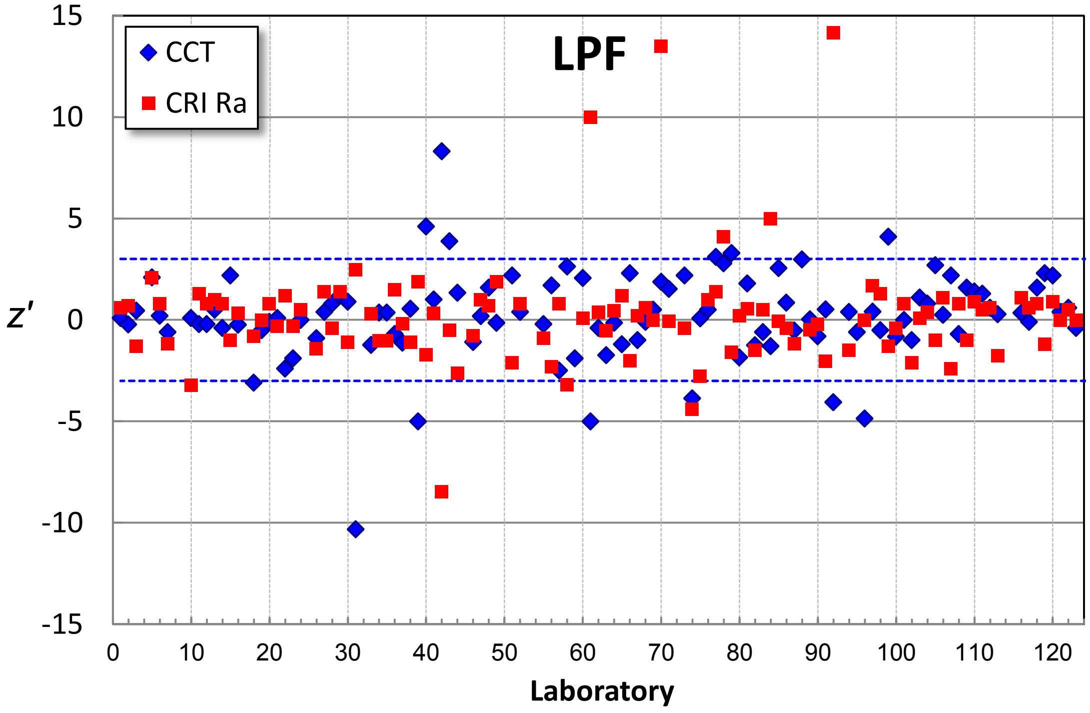


Figure 9-80. z' scores for CCT and CRI R_a for LPF

9.3.3 Summary and Discussion on z’ score results

From Figures 9-73 to 9-76, the z’ scores for I-AC for all quantities are mostly within ± 3 except a few laboratories outside the range. In Figures 9-77 to 9-80, the z’ scores for LPF lamps show significantly more laboratories outside ± 3 range. The z’ scores for RMS current, Figure 9-78, are especially problematic in that too many laboratories are outside ± 3.

Figure 9-81 summarises the percentage of the laboratories that had z’ scores outside ± 3.0 for each artefact type, for all the quantities. Note that, in these results presented in Figure 9-81, the differences among artefact types or quantities appear more enhanced than the differences of variations presented in Figure 9-62.

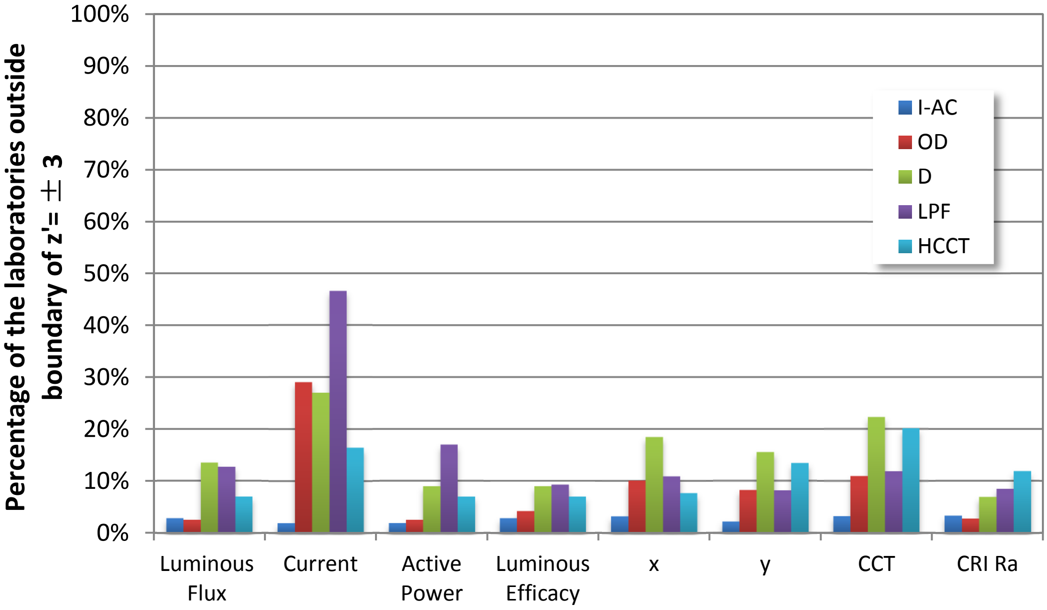


Figure 9-81. Summary of z’ score results – Percentage of the laboratories with |z’| >3

Apparently, the percentages for RMS current are unreasonably high. As discussed in the previous sections, the variations in results for RMS current of LED lamps were much larger than expected, especially LPF lamps. In this case, the denominator in the z’ equation (equation (1) and equation (3)) for RMS current, predetermined in the IC Generic Protocol [4], was too small, leading to too large values of z’. The percentages for colour quantities of the D lamp are also rather high. Only one set of $\hat{\sigma}$ and u_X was determined for all types of LED lamps in the IC Generic Protocol. These values could have been determined for each artefact type separately. These variations for different artefact types should be considered when the Participant Results Reports are evaluated by accreditation bodies.

The z’ score (or a similar metric) is commonly used for testing laboratory accreditation in support of product certification activities. An important point in using z’ score is that the denominator values need to be pre-determined appropriately, thus it requires good knowledge on the expected uncertainties of measurement by participating laboratories for the type of product tested and for relevant quantities in scope. The results of this IC may be utilised for future proficiency testing in setting more appropriate sets of the SDPA values for z' score, while such values may also depend on the purpose of the accreditation.

9.4 E_n numbers

E_n numbers were calculated for all data that included uncertainties of measurement. The numerical values of the E_n numbers were reported in the Participants Results Report issued to each participant, and also in all the figures presented in the IC 2013 Interim Reports issued from each Nucleus Laboratory. In the following sections, the E_n numbers are presented for all quantities measured for two artefacts (I-AC and LPF), representing the least and the most problematic lamps. The dashed lines in each figure show $E_n = \pm 1$, within which the results are generally judged satisfactory.

9.4.1 Incandescent – Alternating Current (I-AC) lamp

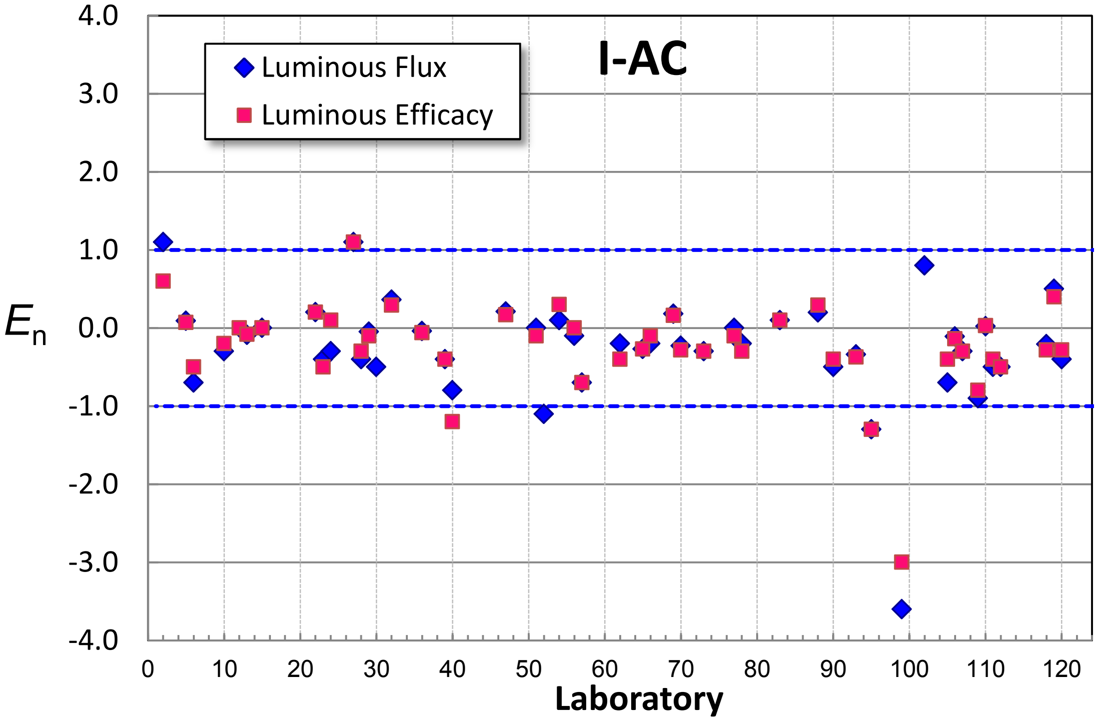


Figure 9-82. E_n numbers for luminous flux and luminous efficacy for I-AC

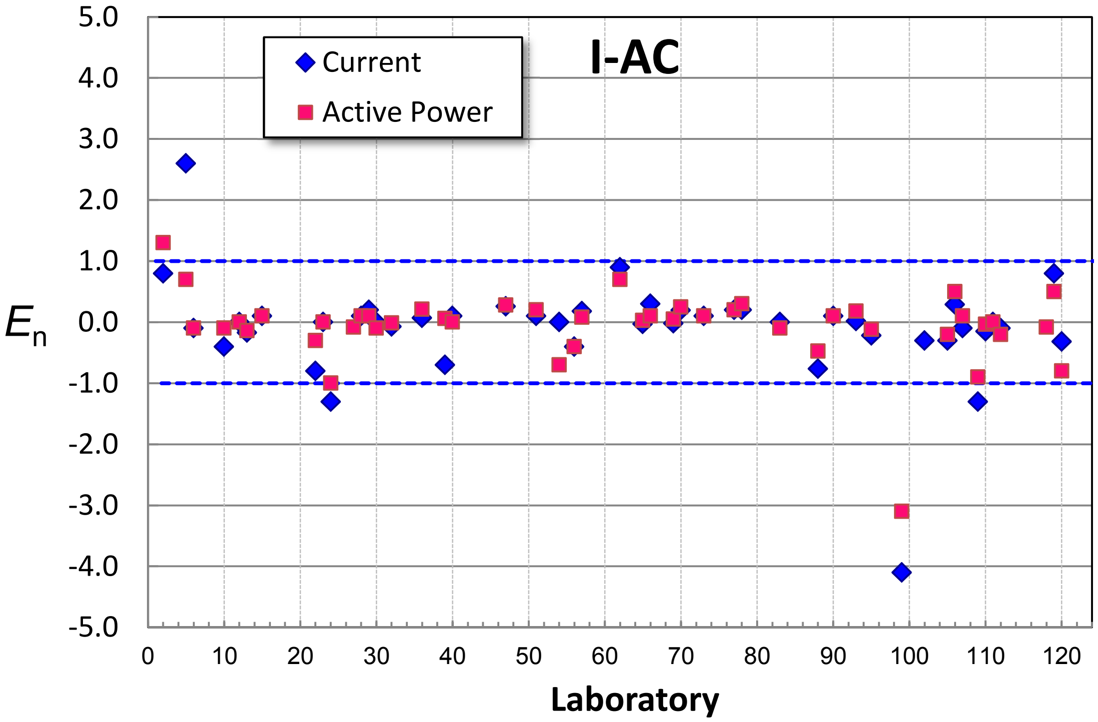


Figure 9-83. E_n numbers for RMS current and active power for I-AC

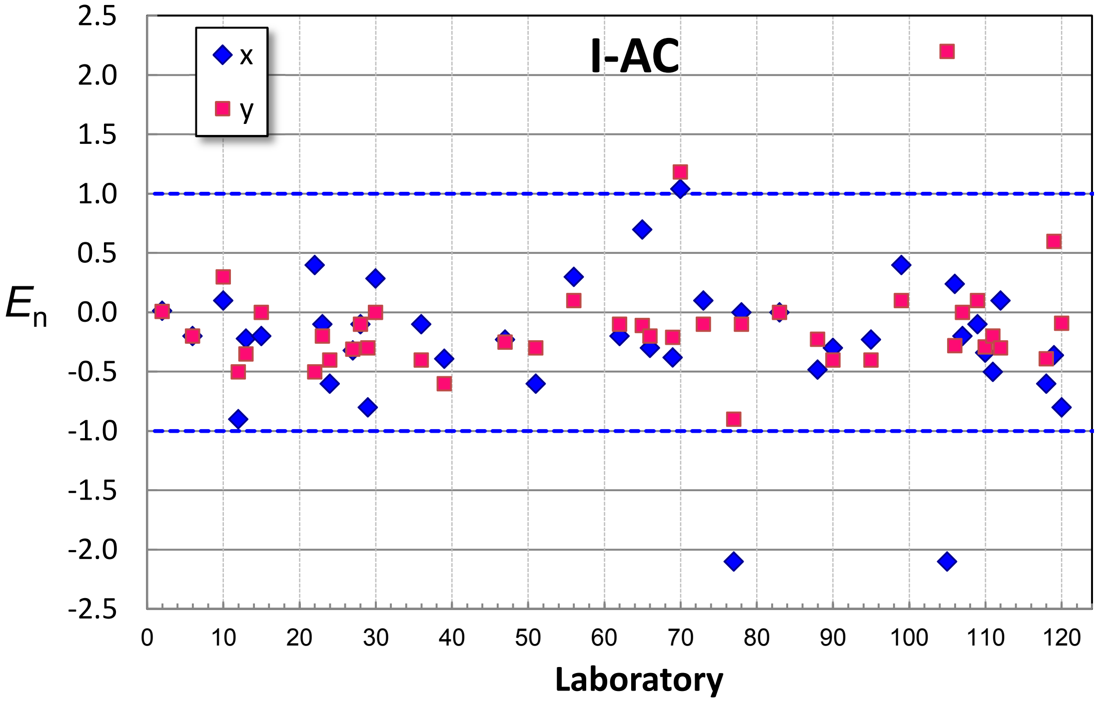


Figure 9-84. E_n numbers for chromaticity x, y for I-AC

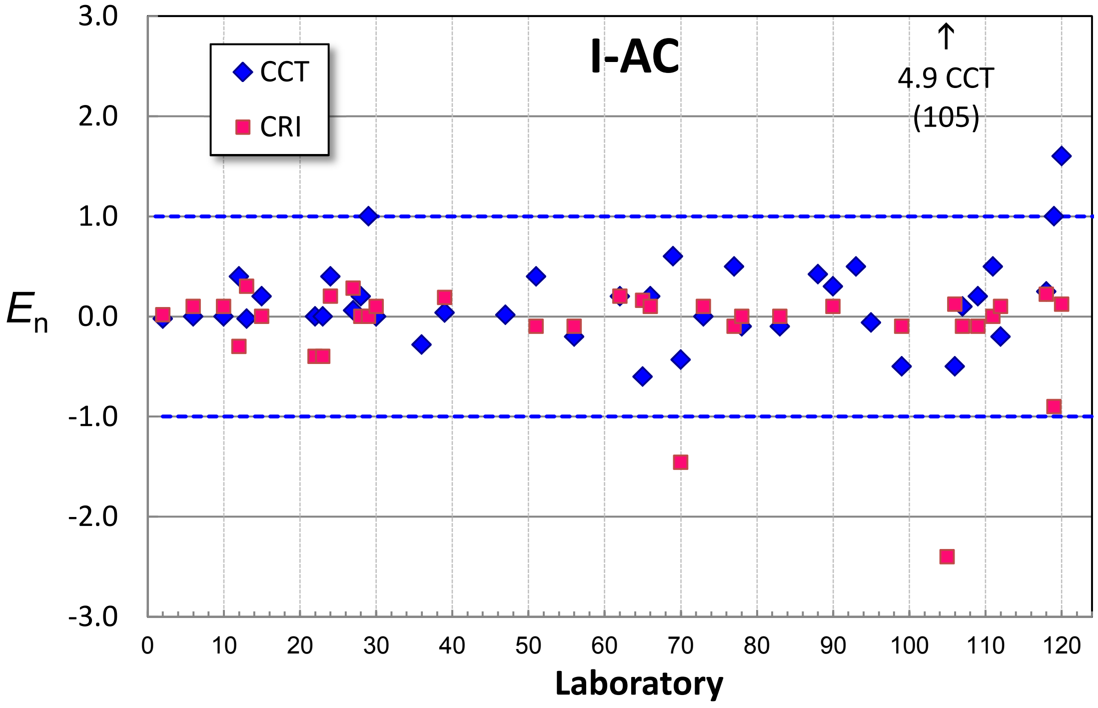


Figure 9-85. E_n numbers for CCT and CRI R_a for I-AC

9.4.2 Low Power Factor (LPF) lamp

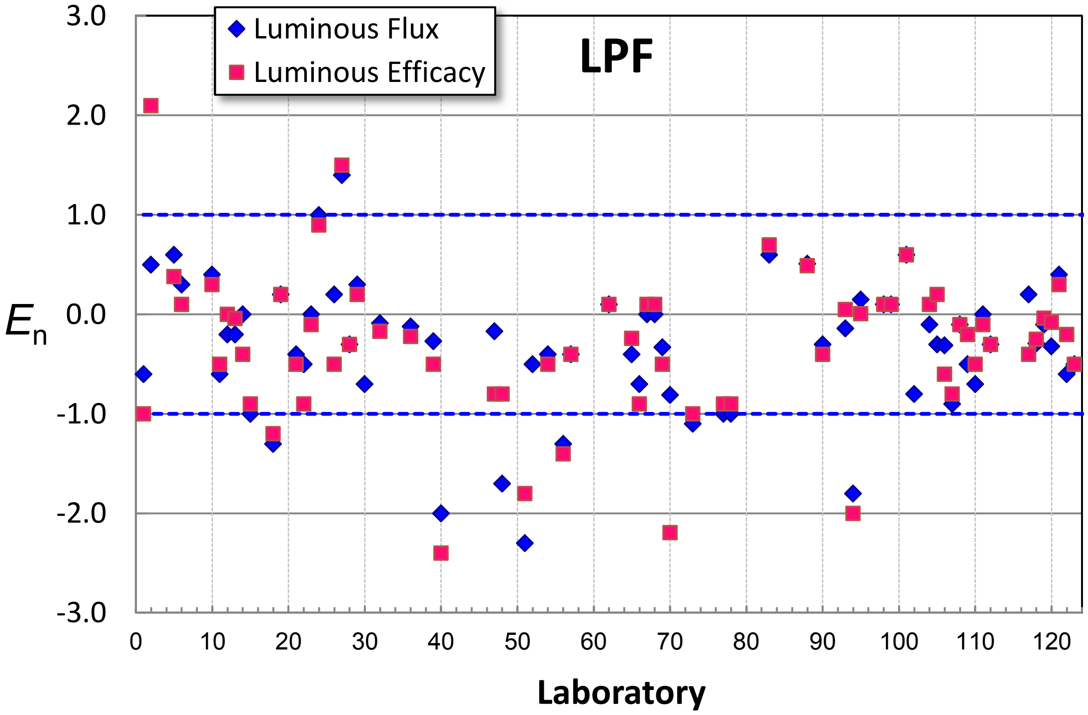


Figure 9-86. E_n numbers for total luminous flux and luminous efficacy for LPF

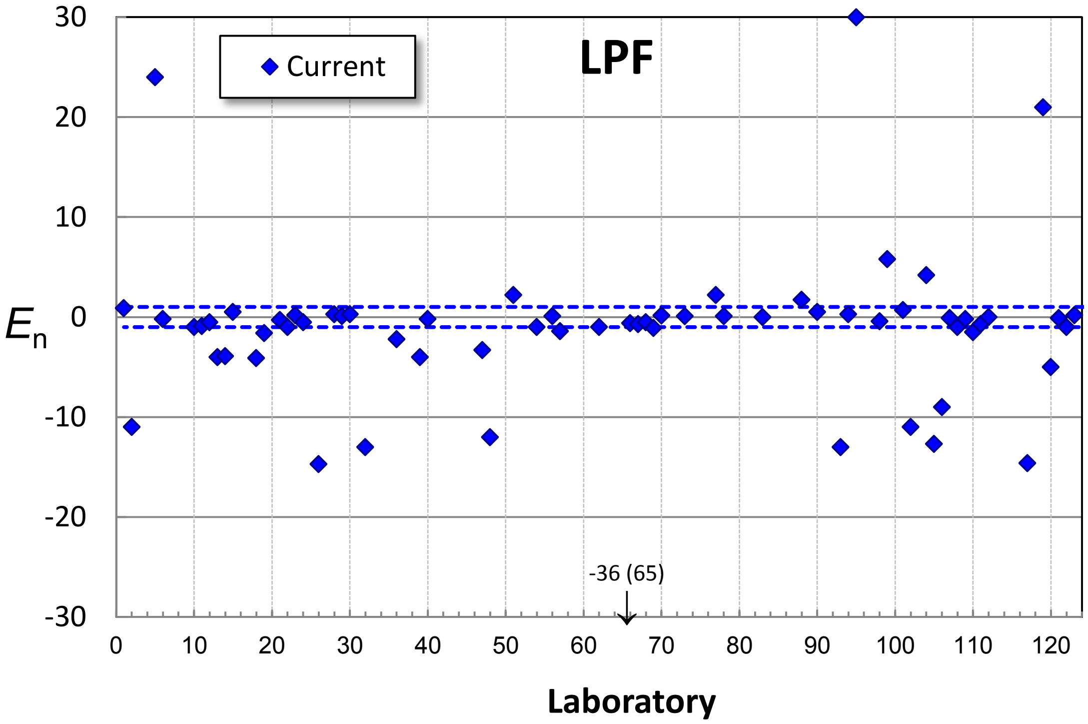


Figure 9-87. E_n numbers for RMS current for LPF

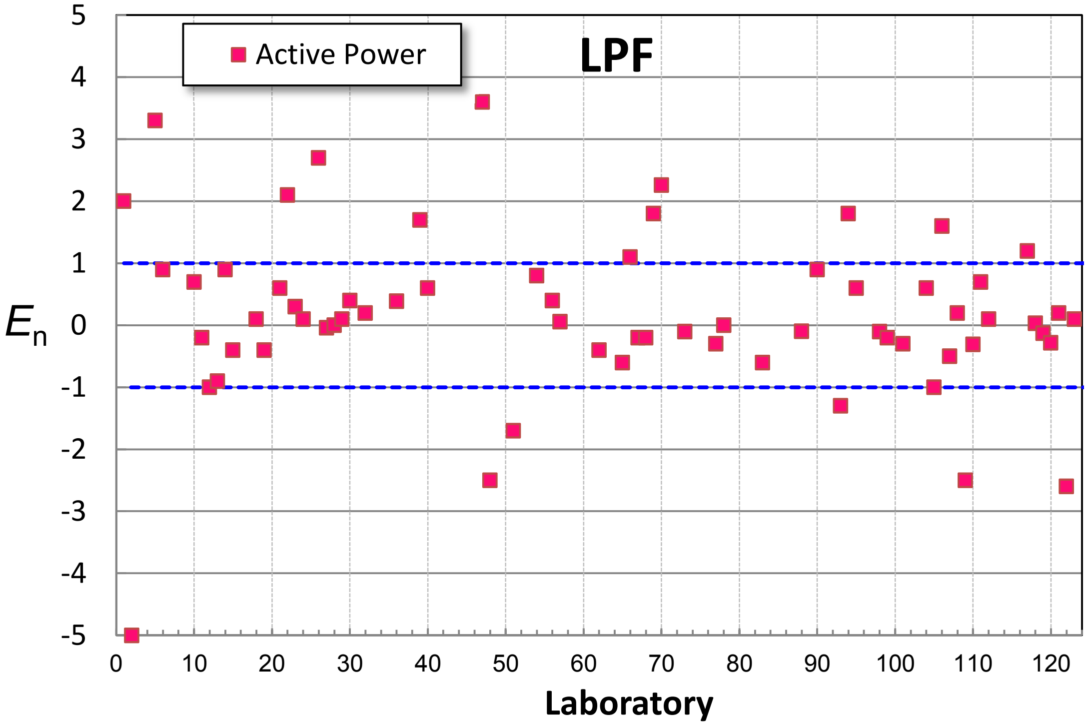


Figure 9-88. E_n numbers for Active Power for LPF

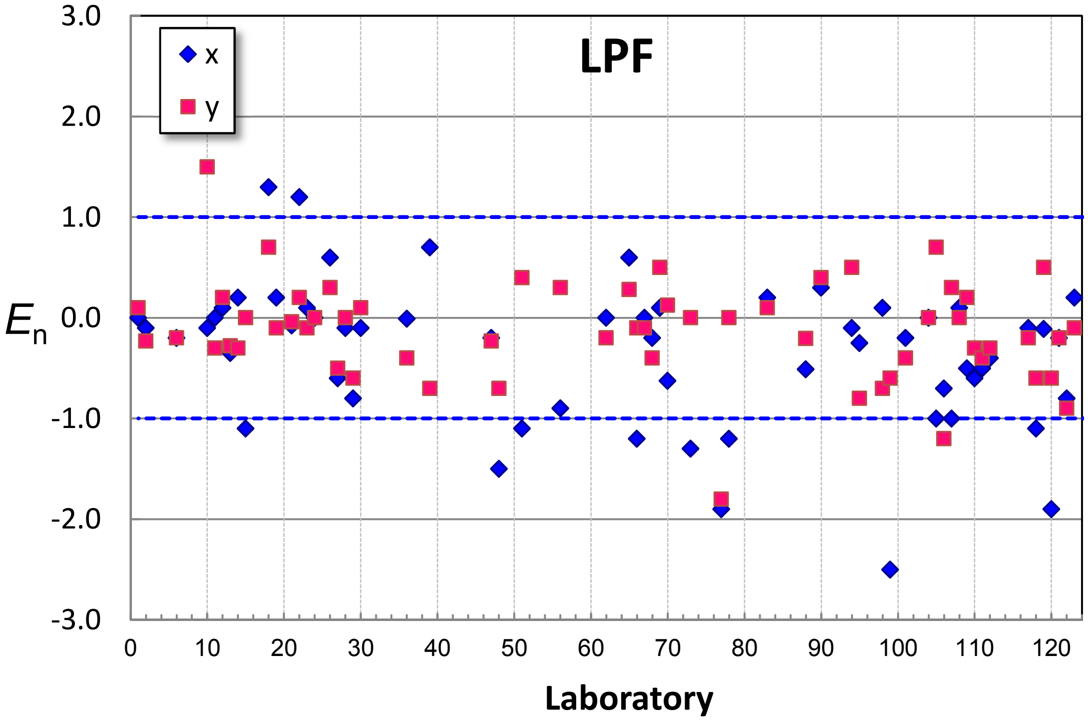


Figure 9-89. E_n numbers for chromaticity x, y for LPF

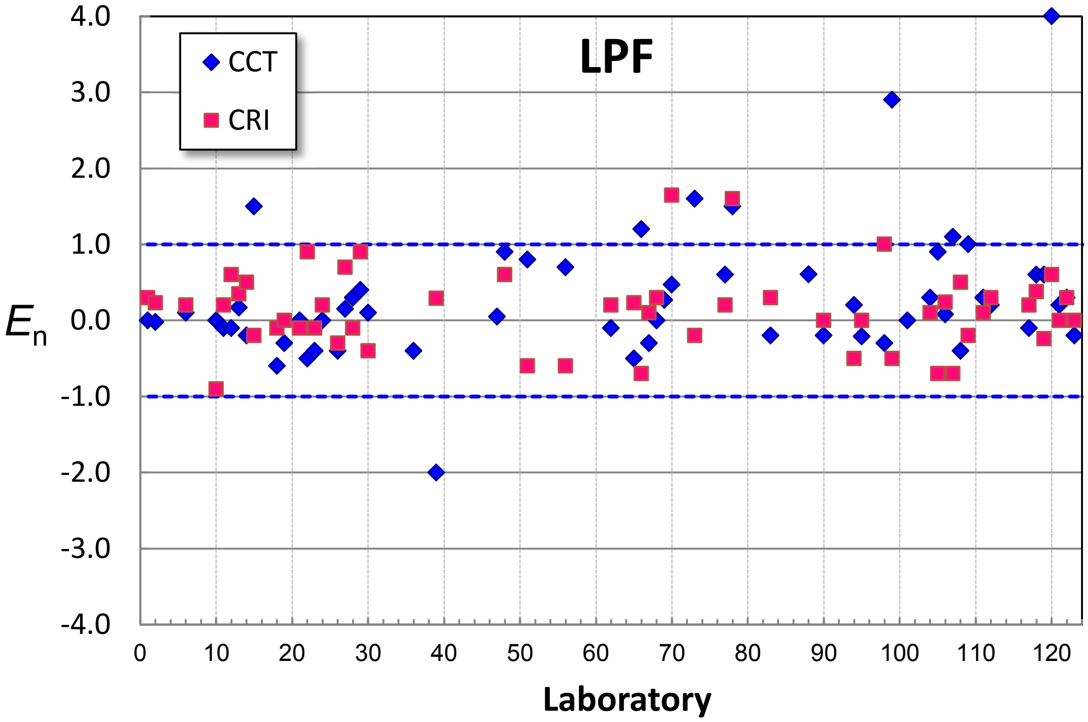


Figure 9-90. E_n numbers for CCT and CRI R_a for LPF

9.4.3 Summary and discussion on E_n number results

The results of E_n numbers shown in Sections 9.4.1 and 9.4.2 are similar to those of z' scores in that there are less problems for I-AC, while the results for LPF are more problematic, especially RMS current. The implications of the high E_n numbers, however, are that the participants (and possibly also the Nucleus laboratory) underestimated the uncertainties.

Figure 9-91 shows the percentages of the laboratories that had E_n numbers outside ± 1.0 for each artefact type, for all the quantities. Compared to Fig. 9-81 for z' scores, it shows similar tendencies, and the overall percentages are higher than expected, indicating that uncertainties were underestimated in significant number of cases.

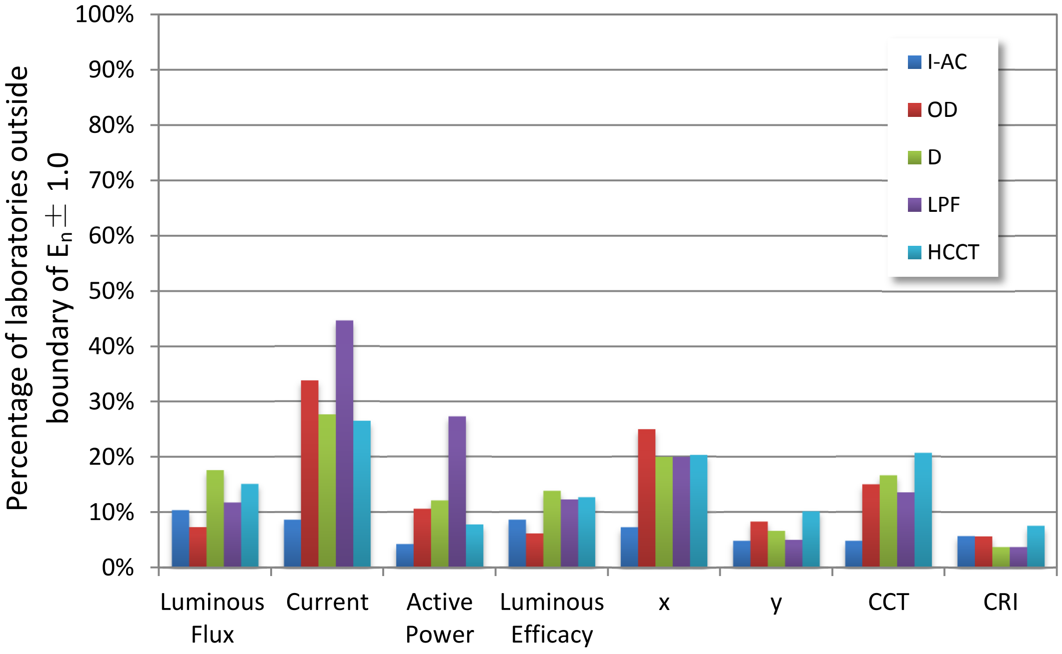


Figure 9-91. Summary of E_n Number results – Percentage of the laboratories with $|E_n| > 1$

A problem with the E_n number, when applied to PT for testing laboratory accreditation supporting product certification activities, is that a laboratory can pass with very large deviations in its results if it claims very large uncertainties. For example, laboratory number 2 in this report has very large deviations from the reference value (11 % for luminous flux for I-AC and 6 % for luminous flux for LPF) but the E_n number is ≈1.0 and 0.5, respectively, and therefore this laboratory will probably pass the E_n check. The z' scores for those two luminous flux measurements by laboratory number 2 were about 8 and 4, respectively, and therefore it would not pass the z' check. As another example, the same laboratory had very large deviations of 0.012 and 0.006 in chromaticity x and y for OD lamp and it would not pass on z' (scores of 9 and 4, respectively) but it would pass on E_n (scores of 0.50 and 0.27, respectively) due to the very large reported uncertainties.

These examples indicate that the use of the E_n number alone can be problematic for testing laboratory accreditation with a purpose of limiting measurement variations among the laboratories, e.g., in support of products certification activities. The E_n number can also be problematic when many laboratories have difficulty in uncertainty evaluation. PTs using the E_n number will become more meaningful for government programmes when they use measurement uncertainty in the programme criteria, however currently, this is not the case.

10 Conclusions

A large scale international interlaboratory comparison, IC 2013 by IEA 4E SSL Annex, was conducted successfully. This IC was designed to be used as proficiency testing for SSL testing accreditation and thus designed in compliance with ISO/IEC 17043. Measurements of photometric, colorimetric, and electrical quantities were compared using at least four different types of LED lamp. IC 2013 included 54 laboratories as direct participants from 18 countries. In addition, the recent results of 35 US laboratories in NVLAP PTs and NIST Measurement Assurance Program were linked to IC 2013. And, data from a further 21 laboratories in the APLAC Proficiency Test T088 were also linked to IC 2013, making it a comparison of test results from 110 laboratories and 123 sets of data.

The results for total luminous flux of LED lamp artefacts measured by most of the laboratories agreed to within ± 4 % (OD) to ± 5 % (D, LPF, HCCT), which is at an expected level of agreement. The results for chromaticity *x*, *y* measured by most of the laboratories agreed to within ± 0.005 for all artefact types, which is also at expected level of agreement. These results verified the levels of the uncertainties estimated for the measurements of these products by laboratories using a well-established test method. It also verified that the test method used in this IC, a consolidation of several available test methods (SSL Annex Interlaboratory Comparison Test Method 1.0 [5]) was effective in limiting the variation in results.

On the other hand, a few extremely large deviations in the results were observed, for example, up to 30 % in luminous flux or up to 0.2 in chromaticity *x, y* in each artefact type. These extreme results must be caused by some major flaws at the participant laboratories in meeting the requirements in the test method. These large deviations by some laboratories demonstrate the importance of proficiency testing, as these laboratories would not have become aware of their problems without participating in such an interlaboratory comparison.

The electrical measurement results also identified some issues. The variations in the results of RMS current for LED lamps were primarily within ± 3 % (OD, D, HCCT) to ± 15 % (LPF) with some deviations much larger than expected (up to 38 %), resulting in high values of z' and E_n for many participants. This result indicates that the generic uncertainty for RMS current to determine the denominator of z' was underestimated, and this should be considered by accreditation bodies when they use these results. The results also indicate that uncertainties reported by many participants were significantly underestimated. However, it was found that the variations in measured RMS current did not affect photometric and colorimetric values significantly, thus it would appear that agreement in RMS current is not very critical. This is explained by the finding that deviations in RMS current were strongly correlated with power factor in the direction to cancel the changes in active power, though not all the cases. The variations in measured power factor were also larger than expected, mostly within ± 0.02 (OD, D, HCCT) to ± 0.1 (LPF). These large variations in the electrical measurements may be caused by differences in the characteristics of the AC power supplies used by the participants, in particular, the output impedance. This is one of the remaining issues for the current test methods for LED lighting products, and future improvements are expected.

The uncertainties reported by the participants were found to be in a very large range (often more than two orders of magnitude) and were often significantly underestimated. Some laboratories reported unreasonably small uncertainties (e.g., 0.0001 in chromaticity *x, y*) or unreasonably large uncertainties (e.g., 10 % in luminous flux or 0.02 in chromaticity *x, y*). Several laboratories (not those linked) did not report uncertainties at all or did not report uncertainties of colour quantities (i.e., chromaticity *x*, *y*, CCT, CRI). These observations indicate that uncertainty evaluation (especially for colour quantities) is still very difficult for the SSL industry, and reported uncertainties are often not reliable. Practical methods and tools for uncertainty evaluation of measurements, as well as educational documents and training for the SSL industry on practical uncertainty evaluation are urgently needed.

In addition to the differences of participants results from the reference values, both z’ scores and E_n numbers were calculated in this IC test, for possible use by ABs. The IC results show that some laboratories would pass on E_n number but fail on z’ score or vice versa. In particular, there were some cases where laboratories claiming large uncertainties would pass on the E_n number though the deviations in their results were very large. Thus, the use of E_n number alone can be problematic when measurement variations need to be limited by the accreditation programme. In practice, the E_n number is suitable for the purpose of assessing the validity of claimed uncertainties (e.g., in *calibration laboratory* accreditation). The z’ score is suitable for the purpose of *testing laboratory* accreditation, which examines a laboratory’s competence and compliance to a test method which is developed to limit measurement variations as is often required in product certification activities. For laboratory accreditation programmes serving both purposes (i.e., serving for product certification activities as well as certifying the reported uncertainties), the use of both the E_n number *and* z’ score would be appropriate. In this study, it was found that the E_n number could be problematic where laboratories had difficulty in uncertainty evaluation, as shown in IC 2013 for colour quantities. And, it was found that the z' score could be problematic if the denominator values were not appropriately specified, as was the case of RMS current measurements in this IC. The results of IC 2013 may be utilised for future SSL proficiency testing using z' score or a similar metric.

This IC test was an attempt to establish a common PT that could serve for accreditation programmes supporting different regulations and government programmes using different regional test methods. For this purpose, the special test method, SSL Annex Interlaboratory Comparison Test Method 1.0 [5], was needed and developed by the SSL Annex. A solution for international harmonisation of SSL testing and accreditation would be to use one international test method for SSL products, which will be published soon by the International Commission on Illumination (CIE). Countries would then choose whether to harmonise to this test method standard based on their own needs and regulatory requirements, enabling worldwide mutual recognition of SSL product testing and laboratory accreditation.

The IC 2013 provided many laboratories in many countries with new knowledge and experience in PT for the measurement of SSL products. It also established a basis to promote SSL laboratory testing accreditation world-wide in support of regulations and government programmes to further accelerate the development of SSL.

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Appendix 1. Uncertainty Budget for $\hat{\sigma}$ and u_X in the calculation of z'

i. Denominator for z'

The generic standard uncertainties were determined by the SSL Annex and are estimated from the measurement conditions and requirements in IEA 4E SSL IC Test Method 1.0 and experience of the Nucleus laboratories. The values for $\hat{\sigma}$ and u_X used in this IC test are shown in Table A1.1

Table A1.1 Generic standard uncertainties and the average standard uncertainties of Nucleus laboratories for calculation of z' score

	Current [%]	**Active power [%]**	**Luminous flux [%]**	**Luminous efficacy [%]**	**Chroma-ticity x**	**Chroma-ticity y**	**CCT [K] (3000K)**	**CCT [K] (6000K)**	**CRI Ra**
$\hat{\sigma}$	0.35	0.45	1.2	1.3	0.0010	0.0011	15	43	0.3
u_x	0.28	0.41	0.61	0.78	0.0010	0.0008	14	41	0.3
$\sqrt{\hat{\sigma}^2+u_X^2+u_{\text{drift}}^2}$	**0.45**	**0.62**	**1.37**	**1.53**	**0.0014**	**0.0014**	**21**	**60**	**0.4**

The values for the CCT for a given artefact should be linear-interpolated or extrapolated based on the two values listed.

ii. Uncertainty budget for $\hat{\sigma}$

$\hat{\sigma}$ is the SDPA (Standard Deviation for Proficiency Assessment) value and was the generic standard uncertainty of a participant's measurement in this IC test. The values of $\hat{\sigma}$ were determined for each measurement quantity. The values of $\hat{\sigma}$are determined as expected uncertainties of measurements by majority of participants using high-quality sphere-spectroradiometer systems, assuming that the participating laboratories meet all the tolerances of test conditions and requirements for instruments specified in IC 2013 Test Method, and that the participants are fairly experienced laboratories and are interested acquiring accreditation for testing of LED lighting products. The tables below show the uncertainty budgets for $\hat{\sigma}$ for each measurement quantity.

Table A1.2 Generic uncertainty budget for luminous flux

Component of uncertainty	Uncertainty contribution
Uncertainty of standard lamp U=1.0% (*k*=2) + aging	0.76%
Spatial integration by integrating sphere or goniophotometer	0.65%
Spectroradiometer error associated with lamp spectrum	0.60%
Operating conditions and reproducibility of test lamp	0.42%
Combined standard uncertainty	1.2%
Expanded uncertainty (*k*=2)	2.5%

Table A1.3 Generic uncertainty budget for AC current

Component of uncertainty	Uncertainty contribution
Calibration of AC power meter U=0.2 % (*k*=2)	0.10%
Errors associated with current harmonics of LED lamp	0.34%
Combined standard uncertainty	**0.35%**
Expanded uncertainty (*k*=2)	0.71%

Table A1.4 Generic uncertainty budget for active power

Component of uncertainty	Uncertainty contribution
Calibration of AC power meter U=0.5 % (*k*=2)	0.25%
Errors associated with current harmonics of LED lamp	0.38%
Combined standard uncertainty	**0.45%**
Expanded uncertainty (*k*=2)	0.9%

Table A1.5 Generic uncertainty budget for chromaticity x, y

Component of uncertainty	Uncertainty contribution	
	x	y
Uncertainty of standard lamp used U=1.0% (*k*=2) + aging	0.0007	0.0007
Spectroradiometer error associated with lamp spectrum	0.0007	0.0008
Operating conditions and reproducibility of test lamp	0.0002	0.0003
Combined standard uncertainty	**0.0010**	**0.0011**
Expanded uncertainty (*k*=2)	0.0020	0.0022

Table A1.6 Generic uncertainty budget for CCT

Component of uncertainty	Uncertainty contribution (K)	
	3000 K	6000 K
Uncertainty of standard lamp used U=1.0% (*k*=2) + aging	11.2	32
Spectroradiometer error associated with lamp spectrum	9.2	26
Operating conditions and reproducibility of test lamp	3.8	11
Combined standard uncertainty	**15**	**43**
Expanded uncertainty (*k*=2)	30	86

Table A1.7 Generic uncertainty budget for CRI Ra

Component of uncertainty	Uncertainty contribution
Uncertainty of standard lamp used U=1.0% (*k*=2) + aging	0.22
Spectroradiometer error associated with lamp spectrum	0.12
Operating conditions and reproducibility of test lamp	0.10
Combined standard uncertainty	**0.3**
Expanded uncertainty (*k*=2)	0.5

iii. Uncertainty budget for u_x

u_x is the standard uncertainty of the reference value. In this IC test, it is determined as the average of uncertainties of measurement of the LED lamps by four Nucleus laboratories reported in the Nucleus Laboratory Comparison Report [3]. The values of u_x for each measurement quantity are determined as shown in Table A1.1. The table A1.8 shows the calculation of u_x

Table A1.8 Uncertainty budget for u_x

		Current [%]	**Active power [%]**	**Luminous flux [%]**	**Luminous efficacy [%]**	**Chromaticity x**	**Chromaticity y**	**CCT [K] (3000K)**	**CRI Ra**
U (*k*=2)	NIST	0.64	0.97	0.70	1.2	0.0020	0.0020	20	
	VSL	0.70	1.22	1.3	1.8	0.0017	0.0006	35	
	NLTC	0.20	0.23	1.5	1.8	0.0027	0.0027	25	
	NMIJ	0.67	0.87	1.3	1.6	0.0014	0.0015	30	
average *U*		0.55	0.82	1.2	1.6	0.0020	0.0017	28	0.50*
average u_x		**0.28**	**0.41**	**0.61**	**0.78**	**0.0010**	**0.0008**	**14**	**0.3**

* This value is from the NIST uncertainty in NVLAP PT, as CRI was not included in the Nucleus comparison.