# Publishable Summary for 15SIB07 PhotoLED
# Future Photometry Based on Solid-State Lighting Products

## Overview

The project addressed the obsolescence of traditional tungsten filament standard lamp technology used in photometric calibrations and the need to support the introduction and uptake of new solid-state lighting (SSL) products. The project developed and validated the basis for a new photometric system based on white light-emitting diodes (LEDs), including new LED illuminants for colorimetry and LED reference spectrum for photometry. New photometric calibration sources and measurement techniques were designed and built, supporting the specific properties of new light sources and detector technology.

## Need

Classical photometry relies heavily on the use of incandescent standard lamps and *V*(*λ*)-filtered photometers as transfer standards in calibrations of luminous intensity, luminous flux and photometer illuminance responsivity. Photometric measurement methods and spectral data of light sources used in colorimetric analysis of light were established long before SSL products became available for general lighting. Due to the phasing out of incandescent lamps and a lack of the standard lamps (which are used in calibrations) available in the market; a clear and urgent need to develop new LED standard lamps for photometry was identified.

As defined by CIE (International Commission on Illumination), an illuminant is an agreed published spectral power distribution of a theoretical light source, used for analysing reflected or transmitted object colours under specified conditions of illumination. Prior to the start of the project, there were only two illuminants defined as standard illuminants used in photometry and colorimetry for calibration purposes. Due to the introduction and uptake of LED lighting and the disappearance of incandescent transfer standard lamps from the market, there was a need to develop new LED illuminants and reference spectra that are more accurate representations of current lighting technologies.

Luminous flux (lm) and active electrical power (W) of new SSL products are measured in order to determine the luminous efficacy (lm/W) and energy classification of the products. Since spectral responsivities of *V*(*λ*)-filtered photometers differ from the defined CIE *V*(*λ*) curve, all photometers are typically calibrated using incandescent light with correlated colour temperature (CCT) of 2856 K. This causes unwanted spectral errors in the measurements of SSL products, as their spectra differ from the spectra of calibration sources. Thus, new LED standard lamps with well-defined spectral power distributions (SPDs) and supporting detector technology are needed to provide convenient and reliable traceability for measurements of SSL products and calibration of photometers to pave the way to lower uncertainties. The objectives of PhotoLED were clearly aimed at addressing the needs mentioned above.

## Objectives

The overall aim of the project was to develop new technology to replace the phasing-out tungsten filament standard lamps used in classical photometry, and to reduce the uncertainties in luminous flux and luminous efficacy measurements of SSL products by developing new LED standard lamps and supporting detector technology. The specific technical objectives of the project were:

1. To develop LED illuminants and LED reference spectra that can complement or replace the CIE Standard Illuminant A in photometric calibrations and in analysis of colorimetric parameters and to evaluate the consequences of the defined new spectra.

2. To develop new LED standard lamps for dissemination and maintenance of the units of luminous intensity, illuminance and luminous flux triggered by the ban on incandescent lamps. The new LED standard lamps will be optimised for compatibility with existing calibration facilities, spectral properties close to the defined LED reference spectra, well-defined angular uniformity, long lifetime and temporal stability of electrical (DC-





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or AC-operation), photometric and colorimetric characteristics to enable low uncertainties in measurements of their photometric and radiometric properties.

3. To develop new photometers and photometric measurement methods that enable illuminance measurement of the new LED standard lamps with uncertainties as low as 0.2 % (*k* = 2) in the primary realisation of photometric units, or in calibrations of photometer illuminance or luminous flux responsivities at NMIs, accompanied by high-end spectral irradiance measurement of the new standard lamps with uncertainties as low as 0.4 %.
4. To reduce the uncertainties of luminous flux and luminous efficacy measurement of solid-state lighting (SSL) products at national metrology institutes to 0.5 % (*k* = 2) and to demonstrate that uncertainties as low as 1 % (*k* = 2) can be achieved in a test laboratory.
5. To facilitate the uptake of the measurement methods developed by the project by the measurement supply chain, ensuring traceability of measurement results to the end users (test laboratories, lighting manufacturers) and contribute to the development of standards by the international standardisation committees (CIE) concerning solid state lighting.

**Progress beyond the state of the art**

For the new LED-based photometric system, new LED illuminants such as defined Spectral Power Distributions (SPD)s of specific types of lighting that provide the basis for comparing images or colours recorded under different lighting conditions, were defined. Based on the LED illuminants analysis, a subset of SPDs was carefully selected as the LED reference spectra which formed the basis for the development of new physical LED standard lamps that could complement the existing incandescent standard lamps in photometric calibrations. Recent studies have shown that the spectral errors in measurements of SSL products could be reduced by a factor of three on average, in testing of SSL products and in field measurements of SSL by utilising two LED standard lamps with warm and cold white spectra in calibrations of photometer illuminance responsivity. Due to the limited spectral bandwidth of white LEDs (approximately 380–850 nm), the illuminance of an LED standard lamp can be measured with novel detector technology without an optical $V(\lambda)$ filter. Instead, the photometric weighting can be made numerically with accurate measurement of the LED spectrum during calibration of photometric instruments for measurements of SSL.

Photometry based on modern LED technology provides an alternative to the classical photometric methods used at NMIs and at test laboratories. The newly developed, white LED based standard lamps have facilitated; the transfer of the units of luminous intensity, illuminance and luminous flux; from NMIs to industrial test laboratories. These new LED transfer standard lamps have also enabled the calibration of photometers and testing of SSL products with lower uncertainties than before, due to the compatiblity of their spectral properties with typical SSL products.

In addition, a new revolutionary fisheye camera method was developed for measuring the angular intensity distribution of SSL products quickly and reliably, while using integrating spheres of test laboratories. By utilising these new methods, it is expected that test laboratories will be able to drastically reduce the spectral and angular errors and measure luminous efficacy of SSL products with uncertainties as low as 1 %.

**Results**

*LED illuminants and LED reference spectra*

A total of 1500 spectral power distributions of white LED products were measured and collected from the partners and stakeholders for the analysis of new LED illuminants and LED reference spectra. The white LED spectra were based on phosphor-converted blue LEDs, which were categorised according to their correlated colour temperatures (CCTs) into 8 different bins between 2700 K and 6500 K. In addition, special shapes including blue hybrid, red, green, blue (RGB) and phosphor-converted violet LEDs were chosen as potential LED illuminants for colorimetry. The project submitted the analysed LED illuminants to TC1-85 of CIE Division 1 for consideration as possible LED illuminants in a revision of the CIE Technical Report no. 15: Colorimetry. The 4$^{th}$ edition of the CIE15 document, with the new LED illuminants, was published in October 2018 and is available from CIE.

Based on discussions with CIE Division 1 and Division 2, it was established that the LED reference spectra used in photometry, should be a subset of the LED illuminants used in colorimetry. On this basis, the LED illuminants were used as the starting point for analysing suitable LED reference spectra for luminous responsivity calibration of photometers based on which of them would lead to the smallest spectral errors in measurements of light with different SPDs. The analysis was carried out using Monte-Carlo simulation, including calculation of spectral mismatch errors for measurements of the 1500 LED products using the relative spectral responsivity data of over 100 real photometers and SPDs of 8 analysed LED illuminants as possible LED reference spectra. The results showed that a single LED reference spectrum with CCT close to 4100 K would lead to the smallest spectral errors on average, when measuring SSL products of different types, reducing spectral errors by a factor of two on average compared to using an incandescent source with the CIE Standard Illuminant A spectrum for calibration of the photometers.

By using two different LED reference spectra in the photometer calibration, the spectral errors would be reduced by a factor of three on average. However, this would require laboratories to invest in two physical calibration sources, morever it would require the end users of illuminance meters to estimate the CCT of light being measured in field and then use that information to select one of the calibration factors available for the instrument. Extending the analysis to account for the possibility of user error in estimating the CCT of light being measured and selecting the correct calibration factor for the measurement, it was evident that the selection of a single LED reference spectrum for calibration of photometers was the optimal solution. This decision drastically simplified the method proposed for the photometric community. Further tests with the 4100 K LED reference spectrum showed that it led to the smallest spectral errors, even in the case of measuring sources other than SSL (including daylight, fluorescent and high-pressure discharge lamps). This analysis was carried out using existing illuminants that have been published in previous CIE Technical Report no. 15: Colorimetry, 3rd Edition. A calibration source with 4100 K LED reference spectrum performed best in all cases, except when measuring incandescent light and one type of discharge lamp. The results of this spectral analysis have been published by A. Kokka *et. al.* [1].

The influence of the LED reference spectrum on the CIE general $V(\lambda)$ mismatch index $f_1$' was studied using the different LED illuminants. The study higlighted that the smallest changes in the calculated $f_1$' values for photometers can be obtained using the 4100 K LED reference spectrum, as compared to the CIE Standard Illuminant A that is currently used in the definition of the mismatch index $f_1$', further supporting the selection of the 4100 K spectrum as an LED reference spectrum. A proposal for an alternative calculation method for the general mismatch index $f_1$', including influence of LED spectra in combination with broadband spectra, was studied and published [2]. The results showed the possiblity to define an alternative mismatch index which has better correlation between the spectral errors in measurements of light of different types and the calculated $f_1$' for the photometer. The new mismatch index was presented to CIE Division 2 for consideration to be taken into use in the future. Based on this extensive investigation, the project selected the 4100 K LED reference spectrum for selection of suitable LEDs for the new LED standard lamps of the project.

The project partners involved in the work of various CIE Division 2 TCs involved in preparation of new technical reports with updated measurement methods have been informed about the LED reference spectrum. These TCs will take into account the possibility of including LED standards lamps in the measurements or calibration of measurement facilities in addition to incandescent sources. The project partners propose that in addition to CIE TC2-90, CIE should consider establishing a new Division 2 TC to focus on investigating the mechanical, optical and electrical properties and related recommendations for physical LED standard lamps. Overall, this objective has been fully met.

*New LED standard lamps for photometry*

The project developed new photometric standard lamps for luminous intensity and luminous flux. Based on the new LED reference spectrum and the expertise of the project's industrial partners, suitable LEDs were selected for the new standard lamps. The mechanical, electrical and optical specifications of the new standard lamps were investigated. For luminous intensity, a source LIS-A consisting of multiple white LEDs with output aperture and luminous intensity similar to those of a Wi41/G standard lamp was developed. The source can be operated with a laboratory DC current source and an external thermoelectric controller (TEC). A total of 8 standard lamps for luminous intensity were constructed, seasoned for 1000 h and fully characterised for their luminous intensity, stability and spectral properties.

The project developed two types of luminous flux standard lamps with E27-base to ensure compatibility with typical integrating spheres and goniophotometers used by laboratories. The new lamps can produce approximately 800 lm of total luminous flux. Lamp A was operated with DC-voltage and included a built-in precision current source as well as, a thermoelectric cooler (TEC) that controls the LED printed circuit board (PCB) temperature by heating the lamp to compensate for the temperature fluctuations of the laboratory. The lamp has been optimised for use in a laboratory with 25 °C temperature, as recommended in CIE S025 standard, with ±4 °C thermal control range. Lamp B operates with 230 V AC voltage and is supplied by an external laboratory AC voltage source. This lamp consists of a constant power AC/DC converter [3]. It is aimed at test laboratories who prefer to calibrate their measurement systems without changing the voltage source or wiring. A total of six lamps of each type were constructed, aged for up to 1000 h, and characterised for electrical, photometric and radiometric properties.

During the project, the new LED standard lamps were used in two inter-comparisons. In addition, the lamps were used in several test measurements to study their general handling and operation in laboratories, in comparison to typical incandescent standard lamps, including the measurement of photometer directional response index $f_2$. The results of both inter-comparisons combined with the experience gained from using the new light sources indicated that LED standard lamps with 4100 K CCT, can be used as transfer standards in photometry and have the potential to be used as replacement for incandescent lamps in the future. As expected, both inter-comparisons showed that the magnitudes of spectral mismatch errors in measurements with filtered photometers decreased to less than half, as opposed to using incandescent reference lamps for system calibration. Furthermore, the return measurements by the pilot laboratories showed that there were practically no changes in the performance of the LED standard lamps due to commercial travel in protected cases, even if they faced several G's of impact during the transport. This is a clear benefit, as compared to incandescent transfer standard lamps that often need to be carried by hand and in person between laboratories. Therefore, this objective was fully achieved.

*New photometers and photometric measurement methods*

New reference photometers based on the predictable quantum-efficient detector (PQED) were developed for operating without optical $V(\lambda)$ filters, accompanied by specially characterised spectroradiometers, to allow illuminance measurement of the new luminous intensity LED standard lamps with uncertainties as low as 0.2 % ($k$ = 2). As a result, new photometers based on commercial photodiodes were manufactured and characterised for spectral responsivity and a new optical method for calibrating the area of the precision entrance aperture of the detectors was tested for the first time. The method was based on scanning the aperture with a laser beam, while the aperture and the detector were moved in front of the laser beam as a single package using a precision linear xy-translator. The new method was compared with existing mechanical and machine vision area measurement methods. The results are in agreement, with the new optical method showing a potential to provide lower uncertainty than the existing methods used, for most aperture area calibrations. Therefore, the new reference photometers can be used for calibration of illuminance responsivity of $V(\lambda)$-filtered standard photometers using LED standard lamps built using the new LED reference spectrum. In the case of the room-temperature PQED, the calibration was carried out directly against the primary standard of optical power.

A comparison of illuminance and luminous intensity of the new luminous intensity LED standard lamp (LIS-A) sources was performed by the NMI project partners between December 2018 and April 2019. Filtered photometers as well as unfiltered detectors (including PQED) with nitrogen flow, were used for the comparison. Two groups of two LIS-A sources were formed and sent to project partners for the comparison measurements. All sources were returned to the pilot of the comparison and remeasured. Results of 3 out of 5, project partners showed very good agreement with measured values within ±0.2 % of the comparison mean value. Results of 2 of the 5 partners indicated larger deviations, up to 0.5 %, which were related to the unfiltered measurement method. It was suspected that the flow speed of nitrogen used with the detectors could have caused the deviation. The results from two out of three project partners with deviations, were treated as outliers since the cause of the deviation was identified and resolved. The final results will be published as a scientific publication and further investigations into the cause for the deviations will be carried out, after the end of the project.

This objective has been met, considering the results of the comparison with conventional filtered detectors showed good agreement between laboratories and indicated that the presented calibration methods included all relevant information for corrections and reasonable determination of the measurement uncertainty.

*Reducing uncertainties of luminous flux and luminous efficacy of SSL products*

The newly developed LED standard lamps for luminous flux have allowed the unit of luminous flux to be transferred from NMIs to test laboratories for calibration of integrating sphere photometers that are used for measuring luminous flux and efficacy of new SSL products. Due to the new LED technology used in the transfer standard lamps, spectral errors in testing of SSL products have been reduced by a factor of 2 on average, when compared to using incandescent standard lamps for the calibration of the photometric system responsivity.

A fisheye camera method was developed as a quick and reliable way to measure the angular intensity distribution of light sources during measurements with integrating spheres. The system consists of a camera module, fisheye lens, port adapter and automated measurement software. The principle of the method, results of the first test measurements and the practical use of the measurement system have been published by A. Kokka *et. al.* [4]. A large measurement campaign with the fisheye camera method was carried out during 2017–2018, measuring different types of LED lamps with several different integrating spheres and goniophotometers. The results indicated that the spatial nonuniformity corrections measured with the fisheye camera method differ from those obtained using goniophotometers by 0.05 % on average, with maximum observed deviation of 0.22 %. The results of the validation measurements have been published by A. Kokka *et. al.* [5].

A comparison of luminous flux and efficacy was arranged with the project partners, including NMIs and test laboratories to validate the use of the new luminous flux transfer standards for calibration of the measurement facilities of the participating test laboratories. In the first comparison round, five NMIs using traditional incandescent lamps for traceability, each NMI measured a set of five commercial LED lamps with different photometric properties. The results from this round were used to characterise and assess the performance of the commercial comparison artefacts and to establish a Comparison Reference Value (CRV) for each lamp artefact. The five commercial artefacts included AC-operated LED lamps covering a range of different CCTs (2700 K, 4000 K and 6500 K) and angular intensity distributions (25°, $2\pi$ and $3\pi$). In the second round, five partner laboratories acting as test laboratories measured the same sets of commercial LED lamps, each using a reference luminous flux LED transfer standard lamp for their traceability. Both DC- and AC-operated luminous flux transfer standards developed in the project were used, depending on the preference of each laboratory. Both comparison rounds were organized in a star configuration.

The total luminous flux values of the new LED transfer standard lamps were first calibrated at National Metrology Institute (NMI) level with an uncertainty of 0.5 % ($k$ = 2), using an absolute integrating sphere that utilised one of the LIS-A luminous intensity standard lamps as a stable external source. In the luminous flux calibration, the external reference luminous flux of the LIS-A source was determined by measuring its illuminance using a PQED without optical filter. The photometric weighing was obtained by spectral measurement of the LIS-A source with a double monochromator spectroradiometer. The light emitted by the LIS-A was then passed into the integrating sphere through a precision limiting aperture for calibration of the sphere photometer responsivity. Both the relative spectral radiant flux and the angular intensity distribution of the new standard lamps were measured using a gonio-spectroradiometer. In the characterisation and calibration measurements, the transfer standard lamps were operated with a stable laboratory grade DC- or AC-source, depending on the lamp type in measurement.

The results of all participating laboratories were consistent within the uncertainties claimed by each participant. Furthermore, for the five NMIs as well as for three test laboratories the unilateral degree of equivalence was within 1 %. The results show the importance of taking into account the spectral and spatial corrections in the measurements of SSL products. Using the LED-based traceability to reduce the spectral mismatch errors combined with the fisheye spatial correction method, luminous efficacy measurements of test laboratories can agree within 1 %. This objective has been fully achieved.

**Impact**

Prior to the development of the LED calibration spectra and standard lamps, a stakeholder workshop was organised in May 2017 at METAS, Switzerland to gather input from CIE and industry. The workshop was arranged during the CIE Tutorial and Practical Workshop on LED Lamp and Luminaire Testing to CIE S025 with a total of 36 participants from test laboratories, instruments manufacturers and people working in CIE TCs. The project participated actively in the CIE 2017 Midterm Meeting on Jeju, Korea in October 2017 by providing 5 presentations and 1 poster on topics related to the new LED illuminants, LED reference spectrum and the new measurement methods under development. In addition, a two-hour workshop and a dedicated meeting was arranged with a total of 30 participants, to agree the start of a new technical committee within CIE, for defining the LED reference spectrum.

The first PhotoLED training session was arranged for the EURAMET TC-PR members in their annual meeting at IPQ, Portugal on 29 January 2019. During this session, the standard lamps for luminous intensity and luminous flux were presented with possibility to operate the lamps by the participants. Additionally, several presentations were given about the results of the project. The project partners presented 7 talks and 2 posters in the CIE 29th Quadrennial Session in Washington DC, USA, in June 2019, including topics covering the development of the new LED standard lamps, validation of the fisheye camera method, definition of photometric quality index and application of LED illuminants in analysis of colour graphic icon for real complex scenes.

In August 2019, the project arranged a key stakeholder event at DTU Fotonik in Roskilde, Denmark. The event consisted of a technical workshop with presentations and a discussion, as well as a hands-on laboratory training session with the light sources and measurement methods developed in the project. The event gathered approximately 25 people from the industry, universities and companies. The topics covered by the workshop and the training included measurement of the illuminance and luminous intensity of the luminous intensity standards LIS-A using unfiltered detectors with nitrogen flow, the fisheye camera method for spatial correction with an integrating sphere and the two luminous flux standard lamps.

*Impact on industrial and other user communities*

This project succesfully investigated new methods to change the way how the lighting industry will utilise photometry in the future. The project demonstrated that classical tungsten filament standard lamps can be replaced by standard lamps based on LED technology that will reduce the spectral errors in measurements of SSL products to 1/2, reduce the stabilisation time and signal noise, offer better stability, robustness and lifetime, for maintaining photometric scales in laboratories and shipping of the lamps between NMIs and test laboratories.

Achieving lower uncertainties in photometric measurements of SSL products benefits the lighting industry and consumers. Once the methods are widely taken into use, manufacturers of SSL products will be better able to rely on the measurement results from test laboratories, thus speeding up product development and enabling better judgement of the performance of new products coming to market. With the development of a coherent and efficient European metrological infrastructure based on LED-based photometric standards, new measuring instruments and supporting measurement methods, as well as written standards, the benefits of SSL products such as energy efficiency, will be assured and market penetration will be increased.

*Impact on the metrology and scientific communities*

This project has contributed to solving the metrological problems caused by phasing out of incandescent standard lamps, and has been leading the investigation of an improved scientific and technical system of photometry for the measurement of LEDs and other SSL products for the benefit of the society, which better reflects the characteristics and requirements of these type of lighting products.

*Impact on relevant standards*

This project has been involved in the work of several CIE TCs to update the existing standards and technical reports which describe the recommended methods used in photometry and colorimetry. The development of the new LED illuminants and LED reference spectrum has been carried out with close connections to CIE since the start of the project, with both Division 1 and 2 included in the discussions. The project has been actively communicating with CIE TC1-85 related to the development of the new LED illuminants. These illuminants are now included in the revision of the CIE15: Colorimetry, $4^{th}$ Edition, enabling colorimetric calculations with LED spectra of different types. The project partners have participated in many TCs of CIE Division 2 to ensure that the introduction of new physical LED standard lamps and supporting measurement methods, including the fisheye camera method, are included in these technical documents. In June 2018, a new CIE Division 2 Technical Committee TC2-90 ‘LED reference spectrum for photometer calibration’ was established to further analyse and publish the LED reference spectrum as a CIE Technical Report. Once the document has been published, commercial LED standard lamps can be manufactured with CIE recommended reference spectrum to complement the Standard Illuminant A in photometer calibrations.

*Longer-term economic, social and environmental impacts*

The results of the project will enable more reliable classification of energy efficiency of lighting products based on SSL technology. When new technologies reach the market, the consumer will have better confidence in the stated performance of the products, i.e. the values printed on the box, thus enabling them to make more informed choices. A sound metrological framework is the backbone of all accurate measurements. Low uncertainties obtained by high quality measurements increase the confidence in the products and enable better differentiation between the characteristics of various products. Achieving lower uncertainties in the testing of SSL products will also result in less waste and reduced costs for manufacturers due to fewer SSL products being erroneously rejected from entering the market because of the use of large guard bands in determining the energy classes of products.

**List of publications**

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| Internal Funded Partners:<br>1 VTT, Finland<br>2 Aalto, Finland<br>3 CMI, Czech Republic<br>4 CSIC, Spain<br>5 Metrosert, Estonia<br>6 BFKH, Hungary<br>7 PTB, Germany<br>8 RISE, Sweden<br>9 VSL, Netherlands | External Funded Partners:<br>10. DTU, Denmark<br>11. ENTPE, France<br>12. Philips, Netherlands | Unfunded Partners:<br>13. INRIM, Italy<br>14. LMT, Germany<br>15. METAS, Switzerland<br>16. OSRAM, Germany<br>17. OSRAM OS, Germany |
| RMG: - | | |