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NEW MEASUREMENT STANDARDS AND METHODS FOR PHOTOMETRY AND RADIOMETRY

Doctoral Dissertation

Jari Hovila

Helsinki University of Technology
Department of Electrical and Communications Engineering
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Helsinki University of Technology
Department of Electrical and Communications Engineering
Metrology Research Institute

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Author Jari Hovila	

Name of the dissertation New Measurement Standards and Methods for Photometry and Radiometry	
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Abstract

Concordance of measurement units is a prerequisite for international trade, telecommunication and scientific co-operation. National Metrology Institutes (NMIs) develop, maintain and compare these measurement units to ensure world-wide consistency. This thesis presents new national measurement standards for luminance, spectral radiance and luminous flux developed at the Metrology Research Institute, which is the NMI for optical quantities in Finland. In addition, evaluation of photometer calibration methods is presented followed by a correction method for illuminance responsivity calibrations of commercial luxmeters.

The units of luminance and spectral radiance are realized using a characterized reference photometer, a spectroradiometer and an integrating-sphere light source. The realization of the unit of luminous flux (lumen) is based on a 1.65-m integrating sphere instead of a goniophotometer. This is one of the first realizations of lumen in the world using the absolute integrating sphere method originally introduced by the National Institute of Standards and Technology (USA). The measurement set-ups and the characterization measurements are presented with comprehensive uncertainty analysis for each unit. Based on the analyses, the expanded uncertainties ($k = 2$) of the units of luminance and luminous flux are calculated to be 0.36 % and 0.47 %, respectively. The measurement uncertainty for the luminous flux is one of the lowest values ever reported. The validity of the claimed uncertainty is tested by international comparison measurements.

Two methods to calibrate a photometer that measures light-emitting diode (LED) sources are evaluated. This pioneering study shows that narrow spectra and challenging intensity distributions of LED-based light sources require thorough characterization measurements for both the photometer and the LED source. The results from these measurements are presented and compared, followed by a recommendation concerning the preferred calibration method.

A diffuser that improves the angular response of a luxmeter also affects the effective measurement plane, leading to substantial errors in calibration if this plane is simply assumed to be at the outermost surface of the diffuser. For the first time, extensive research was carried out to determine the diffuser reference planes of commercial luxmeters. A number of test measurements with three diffusers of different shapes were conducted to find out that in reality the reference planes are located several millimeters inside the diffuser. At short distances, this causes systematic errors of several per cent in the measured illuminance values, greatly exceeding the calibration uncertainties. A correction method based on the true shift of the reference plane is presented to correct the erroneous calibration results.

Keywords Photometry, radiometry, calibration, measurement standard, optical detectors, light-emitting diodes, diffusers

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Preface

The research presented in this thesis has been carried out at the Metrology Research Institute, Department of Electrical and Communications Engineering of the Helsinki University of Technology, during the years 1999 – 2005.

I wish to express my gratitude to the head of the Department of Electrical and Communications Engineering, Prof. Pekka Wallin, for providing me the opportunity to work in this interesting field.

I am most grateful to my supervisor, Prof. Erkki Ikonen, for his guidance, encouragement and support throughout these years.

I would like to thank my co-authors for making the publications possible and the colleagues at the Metrology Research Institute for nice and inspiring working atmosphere. Especially I want to thank my co-authors Dr. Pasi Toivanen and Dr. Petri Kärhä who always had the time and patience for my questions. I also thank Prof. Kai Peiponen and Dr. Kirsti Leszczynski for their efforts as reviewers of the manuscript.

Laboratory technician Seppo Metsälä is acknowledged for his excellent skills in making all kinds of mechanical parts needed for my research work.

I appreciate the financial support by the Centre for Metrology and Accreditation (MIKES), Graduate School of Electrical and Communications Engineering and Graduate School of Modern Optics and Photonics.

Finally, I am deeply grateful to my wife Heli and my children Heta, Aleksi and Amanda for their love and support during these years.

Espoo, September 2005

Jari Hovila

List of publications

The thesis consists of an overview and the following selection of the author's publications.

I. P. Toivanen, J. Hovila, P. Kärhä, E. Ikonen, "Realizations of the units of luminance and spectral radiance at the HUT," *Metrologia* **37**, 527-530 (2000).

II. K. Lahti, J. Hovila, P. Toivanen, E. Vahala, I. Tittonen, E. Ikonen, "Realization of the luminous-flux unit using an LED scanner for the absolute integrating-sphere method," *Metrologia* **37**, 595-598 (2000).

III. J. Hovila, P. Toivanen, E. Ikonen, "Realization of the unit of luminous flux at the HUT using the absolute integrating-sphere method," *Metrologia* **41**, 407-413 (2004).

IV. J. Hovila, P. Toivanen, E. Ikonen, Y. Ohno, "International comparison of the illuminance responsivity scales and units of luminous flux maintained at the HUT (Finland) and the NIST (USA)," *Metrologia* **39**, 219-223 (2002).

V. J. Hovila, P. Kärhä, L. Mansner, E. Ikonen, "Evaluation of calibration methods of a photometer measuring maritime light-emitting diode buoy lanterns," *Optical Engineering* **43**, 170-173 (2004).

VI. J. Hovila, M. Mustonen, P. Kärhä, E. Ikonen, "Determination of the diffuser reference plane for accurate illuminance responsivity calibrations," *Applied Optics* **44**, 5894-5898 (2005).

Author's contribution

All of the publications are results of team work of the contributing scientists.

In Publication I, the author was responsible for the characterization of the spectroradiometer and made the spectral measurements. He also took part in the data analysis, uncertainty analysis, and writing of the manuscript.

In Publication II, the author built the integrating sphere set-up and made most of the measurements. He also participated in the data analysis.

The author had a major contribution in Publication III. He improved the measurement set-up and made all the characterization measurements. He also made the data and uncertainty analyses and prepared the manuscript.

In Publication IV, the author made the luminous flux measurements and assisted in the illuminance responsivity measurements. He analyzed the luminous flux comparison results and prepared the manuscript.

The author had the main responsibility in preparing Publication V. He carried out all the measurements and data analysis and evaluated the results. He also prepared the manuscript.

In Publication VI, the author examined the correction method and made some of the measurements. He also took part in the data analysis and prepared the manuscript.

List of symbols

A	aperture area
d	measurement distance
D_{eff}	effective measurement distance
D	diameter of a diffuser
E_v	illuminance
f	luminous flux correction factor
F	spectral mismatch correction factor
I_v	luminous intensity
k	coverage factor
K_{m}	maximum spectral luminous efficacy of radiation for photopic vision
L	depth of a diffuser
L_v	luminance
$L_{v,c}$	calculated luminance
$L_{v,m}$	measured luminance
$L_e(\lambda)$	spectral radiance
n	normalization factor
r_1	radius of the sphere source aperture
r_2	radius of the detector aperture
$S_{\mathrm{A}}(\lambda)$	relative spectrum of a CIE standard illuminant A
$s_{\mathrm{rel}}(\lambda)$	relative spectral responsivity of a photometer
$S_{\mathrm{t}}(\lambda)$	relative spectrum of an LED lantern
$V(\lambda)$	luminous efficiency function for photopic vision
W	width of a diffuser
Δd_{P}	distance offset of a photometer
Δd_{S}	distance offset of a light source
ε	polar angle
η	azimuthal angle

Φ_{ext}	reference luminous flux
Φ_{int}	luminous flux of a test lamp
Φ_v	luminous flux
Ω	solid angle

List of abbreviations

BIPM	Bureau International des Poids et Mesures
CIE	Commission Internationale de l'Eclairage
CGPM	Conférence Générale des Poids et Mesures
CCPR	Comité Consultatif de Photométrie et Radiométrie
HUT	former abbreviation for Helsinki University of Technology, Finland
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IEN	Istituto Elettrotecnico Nazionale, Italy
NIST	National Institute of Standards and Technology, USA
NMI	National Metrology Institute
NPL	National Physical Laboratory, UK
PTB	Physikalisch-Technische Bundesanstalt, Germany
SI	Système International d'Unités
SP	Swedish National Testing and Research Institute
TKK	current abbreviation for Helsinki University of Technology, Finland
CMC	calibration and measurement capabilities
FWHM	full width at half maximum
LED	light-emitting diode
TFT	thin film transistor

Table of contents

1. Introduction

1.1. Background

When the 11th General Conference on Weights and Measures (Conférence Générale des Poids et Mesures, CGPM) in 1960 adopted the International System of Units (Système International d'Unités, SI) [1], the development of photometric and radiometric quantities was not progressing very rapidly. At that time, people in this field had already abandoned standard candles, flames and incandescent filament standards [2]. The first well-defined standard source in use, developed in 1948, was based on the luminance of a well-defined Planckian blackbody radiator at the temperature of freezing platinum [3]. Such a device, however, was difficult to use and expensive. Therefore, not very many national metrology institutes (NMIs) acquired it.

It was not until 1979, when the definition of the candela, unit of luminous intensity I_v, was re-defined by the 16th CGPM [4]. The new definition made it possible to realize photometric and radiometric quantities by constructing cost-efficient detectors with known responsivity, potentially allowing more precise measurements also for NMIs with smaller budgets. The uncertainty related to detector characterization decreased and went below the uncertainties associated with the blackbodies due to the development of the cryogenic radiometer [5, 6, 7] and the trap detector [8].

Nowadays many NMIs around the world are using detector-based methods in their realizations of the photometric and radiometric quantities [9, 10, 11, 12, 13, 14, 15 16, 17, 18, 19, 20, 21]. However, detector-based realizations do not obviate standard lamps, since reliable light sources are always needed in practical calibrations. Standard lamps are also used for maintenance purposes. Periodic calibrations of a group of standard lamps provide information about the long-term stability of the realized unit.

International intercomparisons between NMIs are arranged for all applicable quantities. Reason for such comparisons is to check that each participating NMI is capable of measuring certain quantities within claimed uncertainties. Comparisons can be bilateral or trilateral [22, 23], or even worldwide where approximately 10-20 NMIs take part. Such large comparisons are usually key comparisons [24] arranged by the Consultative Committee for Photometry and Radiometry (Comité Consultatif de Photométrie et Radiométrie, CCPR) and the International Bureau of Weights and Measures (Bureau International des Poids et Mesures, BIPM).

The first light-emitting diode (LED) emitted red light and was developed in 1962 by Nick Holonyak Jr. working at the Advanced Semiconductor Laboratory of the General Electric Co [25]. The invention of the red LED was followed by the development of green [26] and yellow [27] LEDs in the early 1970's. They were used in small displays and for indication purposes. It was not until during the 1990's, when the first blue [28] and white [29] LEDs were developed. This was a start for the solid-state lighting. As efficiency (the ratio between light output and consumed electric power, lm/W) of the white LEDs has improved, they have become a strong challenger for incandescent lamps. LEDs of various colors are nowadays used in large displays, traffic lights and signs, advertising signs and in decorative lighting, just to name a few applications.

From the photometric and radiometric point of view, LEDs are much more difficult light sources to characterize and measure than incandescent lamps. LEDs have usually narrow spectral features and their light output is limited to a small solid angle [30]. International Commission on Illumination (Commission Internationale de l'Eclairage, CIE) is working to improve the existing standards [31] for LED measurements [32, 33]. The unique properties of the LEDs set additional requirements for the detector characterization. In order to measure precisely the amount of light emitted by the LED, the spectral responsivity of a photometer or radiometer has to be measured [34]. It is also absolutely necessary to measure the emission spectrum of the LED.

Commercial illuminance meters (luxmeters) are often used in applications where the light coming from a wide angle needs to be measured. A white diffuser in front of the detector inside the measuring head is an easy way to improve the angular responsivity. When such a meter is calibrated, the calibration distance is typically measured from the outermost surface of the diffuser. The actual distance reference plane might be inside the diffuser and the calibration will be erroneous [35]. Since the manufacturers usually do not give any information concerning the reference plane offset, it has to be measured separately for each type of diffuser.

1.2. Progress in this work

The units of luminous intensity, illuminance and spectral irradiance were successfully realized at the Helsinki University of Technology (TKK) [14, 17, 36] before the research work in this thesis was started in 1999. These realizations provided traceability to subsequent realizations of photometric and radiometric quantities, luminance and spectral radiance [Publ. I], which are introduced in Chapter 2. Today, the realization of spectral radiance provides traceability for computer and mobile phone thin-film-transistor (TFT) display characterization measurements. To ensure proper readability of such displays, the accuracy and reliability of these measurements are very important.

Chapter 2 also includes the description of the realization of luminous flux, which is a very essential photometric quantity for the lighting industry. The development work for the realization began already in 1997 [37]. Preliminary studies showed that, instead of miniature lamps, high-intensity LEDs can be used as light sources in the sphere characterization. The measurement set-up, based on 1.65-m integrating sphere, was constructed and first test measurements were conducted to show that the sphere system works as expected [Publ. II]. During the next years, the measurement set-up was further improved and the realization of the unit of luminous flux was finalized in 2004 [Publ. III]. The long-lasting, determined work to build a Finnish national standard for luminous flux resulted in a measurement system which has one of the lowest measurement uncertainties (0.47 %) in the world. The leading NMIs, National Institute of Standards and Technology (NIST, USA), National Physical Laboratory (NPL, UK) and Physikalisch-Technische Bundesanstalt (PTB, Germany) have earlier reported corresponding uncertainties of 0.53 %, 0.35 % and 0.60 %, respectively, in their trilateral intercomparison [23]. The results of the comparison measurements agreed within these uncertainties.

An overview of international intercomparisons included in this thesis is provided in Chapter 3. TKK and NIST arranged a bilateral comparison for illuminance responsivity and luminous flux in 2000 [Publ. IV]. Results showed that measurements of both quantities were in excellent agreement, having differences less than 0.1 %. Similar results were obtained from the test measurements with Swedish National Testing and Research Institute (SP) when their luminous flux lamps, traceable to calibration at BIPM in 2001, were measured at the TKK in 2003 [Publ. III]. Average difference less than 0.2 % was observed, providing further confidence in the low measurement uncertainty of the unit of luminous flux at the TKK.

A commercial photometer measuring a light source based on light-emitting diodes was brought to TKK for illuminance responsivity calibration in 2002. Because LED-based sources are difficult to measure even with laboratory-grade equipment, it was considered necessary to compare two different calibration methods [Publ. V] using both lamps and LEDs as light sources. The problems with LEDs as compared to incandescent lamps and the calibration methods themselves are described in Chapter 4. Issues like measurement geometry, light source characteristics and later upgrading of the measurement system were used as criteria to evaluate which method had more advantages. A discussion about the reasons why a particular method was found better is also included in Chapter 4.

From photometric devices, commercial illuminance meters (luxmeters) are most often brought for calibration at TKK. With a few exceptions, these meters are equipped with diffusers to widen the measurement angle and improve the cosine response. During the calibration, the outermost surface of the diffuser is placed to the same distance from the light source as the reference detector at each illuminance level. Since the illuminance changes with distance, it was seen important to study, how far inside the diffuser the actual distance reference plane is [Publ. VI], because that has a direct influence on the results of the calibration. As described in Chapter 5, luxmeters with diffusers of three different shapes were tested by measuring illuminances at several distances from a standard lamp and comparing the results with a reference detector without a diffuser. The distance reference planes were determined for each diffuser and correction factors were calculated to mathematically shift the reference planes to the right locations. As a result, the systematic calibration errors up to 2 % due to diffuser reference planes disappeared. Only statistical variations of the order of 0.2 % remained, improving the calibration accuracy by an order of magnitude.

2. Realizations of the units

Basically detector-based realization is a development process to construct, characterize and maintain a stable detector for a certain unit of measurement. The realized unit must be traceable to a base unit of the SI system either directly or through previously realized units. At TKK the primary standard for photometric measurements is a reference photometer consisting of a trap detector, a temperature-controlled $V(\lambda)$ filter and a precision aperture [17]. All of the components can be characterized separately [38, 39, 40]. The realization must also include thorough and reliable uncertainty analysis, which is compiled by following certain guidelines [41, 42]. The square root of the sum of squares of the individual uncertainty components is multiplied by a coverage factor k to obtain a relative expanded uncertainty value. The most commonly used coverage factor, $k = 2$, means that the "real" value is inside the expanded uncertainty limits with 95 % probability[1].

2.1. Luminance and spectral radiance

Luminance L_v is the photometric counterpart of spectral radiance $L_e(\lambda)$, which is defined as the radiant power per unit area, unit solid angle and wavelength interval ($W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}$). Luminance describes the brightness of a surface as seen by a human eye. As luminance and spectral radiance are source-related quantities, they do not depend on the measurement distance. Luminance and spectral radiance are linked by

$$L_v = K_m \int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} L_e(\lambda)\, V(\lambda)\, \mathrm{d}\lambda\,, \tag{1}$$

where $V(\lambda)$ is a spectral luminous efficiency function for photopic vision standardized by the CIE. The $V(\lambda)$ function describes the responsivity of a human eye in daylight conditions [43]. Maximum spectral luminous efficacy of radiation

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[1] All expanded uncertainty values in this thesis use a coverage factor $k = 2$.

for photopic vision K_m is a scaling factor providing a link between radiometric and photometric quantities and has the value of 683 lm/W [43].

The TKK realizations of luminance and spectral radiance are based on an integrating-sphere source having a diameter of 30 cm. Light from the external lamps enters the sphere and after numerous reflections from the high-reflectance coating (Spectraflect®, [44]) inside the sphere, uniform intensity distribution at the output precision aperture is produced. The luminous intensity of the sphere output is measured using the TKK reference photometer [17]. It is calibrated on regular basis for optical power using several laser wavelengths with a cryogenic radiometer [18], which provides traceability to the SI base unit of electric current, ampere (A) via electric power.

Because the measurement distance is relatively short (800 mm) as compared to the aperture diameters, a correction for the physical distance is needed. The effective measurement distance D_{eff} can be calculated as

$$D_{\mathrm{eff}} = \sqrt{r_1^2 + r_2^2 + d^2}\,, \tag{2}$$

where r_1 is the radius of the sphere aperture (8 mm), r_2 is the radius of the detector aperture (1.5 mm) and d is the physical distance between the apertures [45].

Luminous intensity I_v is derived from the measured illuminance E_v and the effective measurement distance. Since luminance is defined as the luminous intensity per unit area (cd m^{-2}), it can be obtained as

$$L_v = \frac{E_v \cdot D_{\mathrm{eff}}{}^2}{A}\,, \tag{3}$$

where A is the area of the sphere aperture.

The uniformity of the light at the output of the sphere is very important but finding a suitable measuring device for this purpose with adequate resolution is almost impossible. Even with the best CCD-cameras it would be difficult to distinguish the non-uniformity of the light at the sphere output from the non-uniformity of the CCD-matrix of the camera. Fortunately, the light path through the aperture is reversible and uniformity can be measured in an alternative way. The two light sources were removed from the sphere and large-area photodiodes were put into their places. The uniformity was measured by scanning the output of the sphere with a laser beam and the currents from the photodiodes were recorded. As a result, the spatial uniformity of the sphere aperture was determined [Publ. I].

Spectral radiance can be measured directly by using a radiance meter. In order to calibrate a radiance meter, a source with known spectral radiance is needed. At TKK, the spectral radiance of an integrating sphere source is obtained from the measured luminance by taking advantage of the link between the two quantities as presented in Eq. (1). The only additional procedure is that the relative spectral irradiance of the sphere source has to be measured by a calibrated spectroradiometer. Using Eq. (1) a luminance value using the measured spectrum is calculated and compared against the measured luminance to obtain a normalization factor

$$n = \frac{L_{v,m}}{L_{v,c}}, \tag{4}$$

where $L_{v,m}$ is the measured luminance and $L_{v,c}$ is the calculated luminance. Spectral radiance is then obtained by multiplying each spectral component with the normalization factor [Publ. I].

Typical measurement set-up for luminance and spectral radiance measurements is presented in Figure 1.

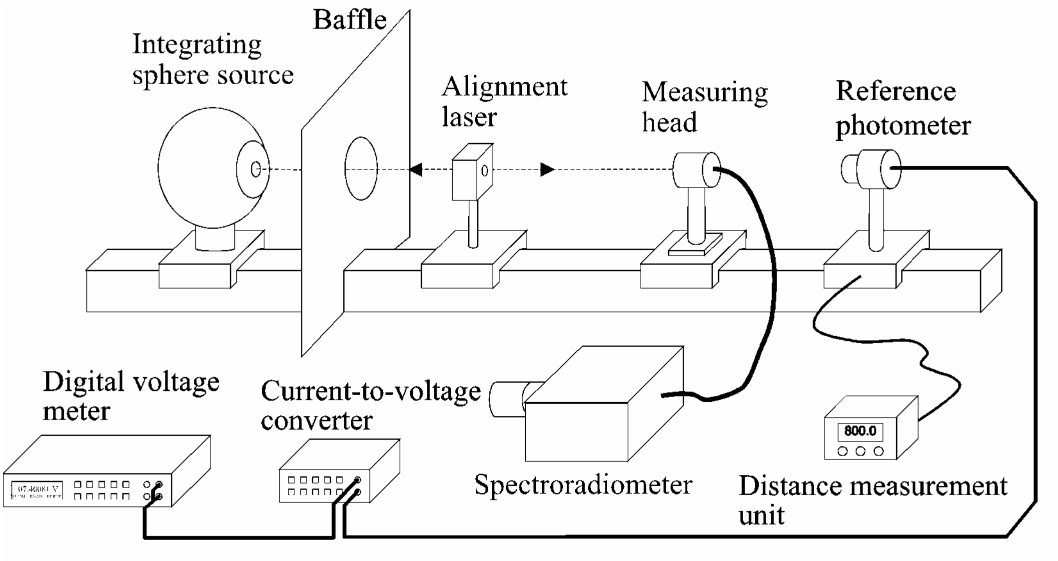

Figure 1. The measurement set-up for luminance and spectral radiance measurements. The alignment laser is removed from the rail when luminance or spectral radiance is measured.

Devices are aligned to the same optical axis with a two-beam alignment laser. The baffle between the integrating sphere and the detectors is used to prevent stray light. Photocurrent from the photometer is taken to a current-to-voltage converter, which works as a transimpedance amplifier. Resulting output voltage is recorded using a digital voltage meter.

The measuring ranges of the units of luminance and spectral radiance at the TKK are 250 – 40000 $cd \cdot m^{-2}$ and 0.0001 – 1 $W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}$, respectively. According to the uncertainty analysis presented in [Publ. I], the relative expanded uncertainty of the realization of the unit of luminance is 0.36 %. For the unit of spectral radiance, the relative expanded uncertainty varies between 0.60 % and 2.50 % in the wavelength region from 360 nm to 830 nm. During this thesis work, there have not been any international intercomparisons for luminance or spectral radiance. Nevertheless, these quantities have been accepted to the Calibration and Measurement Capabilities (CMC) database maintained by the BIPM [46], due to the comparison evidence of luminous intensity [22], illuminance responsivity [47] and spectral irradiance [48].

2.2. Luminous flux

Luminous flux (unit: lumen, lm) is a photometric quantity that describes the total optical power of a light source as seen by the human eye. Typically, a 60-W white incandescent lamp produces about 700 lm. Traditionally luminous flux primary standard lamps have been calibrated using a goniophotometer [20, 49, 50, 51], where an illuminance standard photometer is precisely moved around the lamp at a known distance. Illuminance values $E_v(\varepsilon,\eta)$ are measured over the solid angle $\Omega = 4\pi$ and integrated. The luminous flux Φ_v is calculated as

$$\Phi_v = r^2 \int_0^{\pi} \int_0^{2\pi} E_v(\varepsilon,\eta) \sin(\varepsilon)\, \mathrm{d}\varepsilon\, \mathrm{d}\eta\,, \tag{5}$$

where r is the measurement distance, ε is the polar angle and η is the azimuthal angle of spherical coordinates.

In addition to luminous flux, the method also gives the spatial intensity distribution of the lamp, which is clearly an advantage. However, this kind of measurement set-up requires a large facility and accurate positioning devices. Additionally, an integrating sphere has to be used, if secondary standard lamps are calibrated using the primary lamps as reference standards.

An alternative absolute measurement method to goniophotometric method that uses only a large integrating sphere was developed at the NIST in 1995 [21, 52, 53]. The method was successfully tested by calibrating luminous flux standard lamps using both methods in Istituto Elettrotecnico Nazionale (IEN, Italy) in 1996 [54]. Despite the promising results, the IEN still calibrates luminous flux standard lamps only with a goniophotometer. A couple of years later, the BIPM conducted experiments to calibrate luminous flux standard lamps in collaboration with the NIST with extended measurement set-up [55]. Unfortunately, the development work discontinued as the photometric and radiometric section of the BIPM was shut down in 2004. Therefore, the TKK is the second NMI in the world that has fully implemented a setup for luminous flux measurements based on the absolute integrating sphere method [Publ. II, Publ. III].

The absolute integrating sphere method is based on an external lamp to produce a reference flux which is compared to the luminous flux of the lamp inside the sphere. The measurement set-up at the TKK is presented in Figure 2. The measuring range of the set-up is 10-10000 lm.

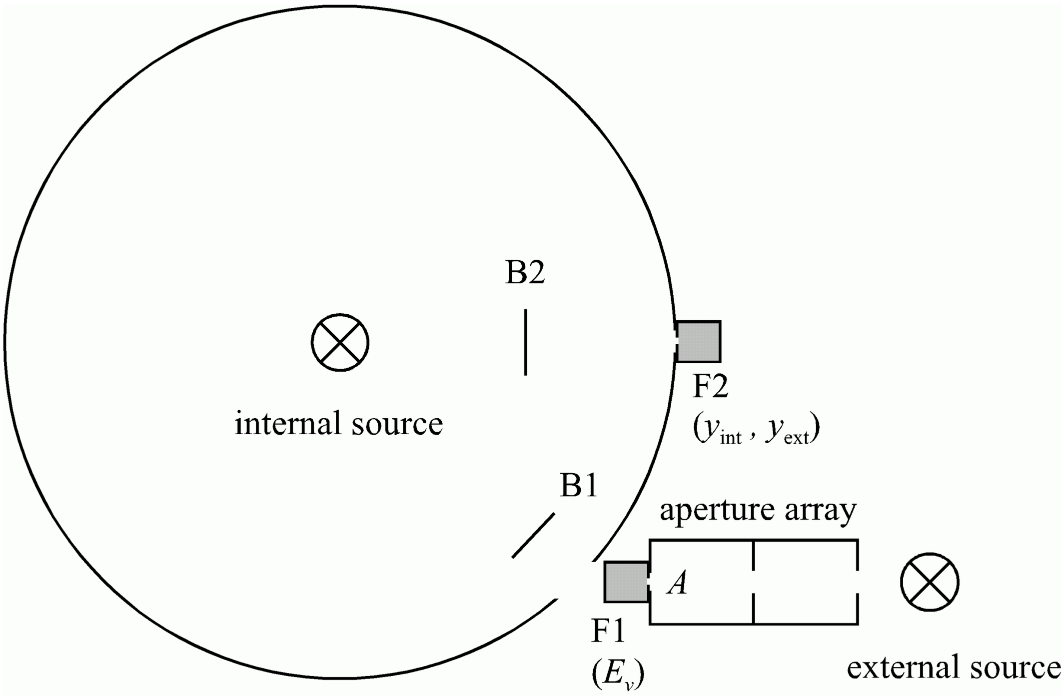

Figure 2. The luminous flux measurement set-up. F1 and F2 are photometers, and B1 and B2 are baffles [Publ. III].

The sphere has the same coating material at the inner surfaces as the luminance/spectral radiance sphere. The external source (1-kW FEL type lamp operated at a correlated color temperature of 2856 K) produces illuminance E_v at the precision aperture plane. The illuminance is measured with the standard photometer F1. Reference luminous flux Φ_{ext} can be calculated as

$$\Phi_{ext} = E_v A, \tag{6}$$

where A is the area of the aperture.

When the photometer F1 is removed, the reference luminous flux produces signal y_{ext} from the photometer F2 attached to the sphere wall. When the internal source (Osram Wi40/G GLOBE operated at a correlated color temperature of 2750 K and producing about 2200 lm) is operated, another signal y_{int} is recorded from the photometer F2. Luminous flux of the internal source is then obtained as

$$\Phi_{\text{int}} = f \cdot \frac{y_{\text{int}}}{y_{\text{ext}}} \Phi_{\text{ext}}\,, \tag{7}$$

where f is a correction factor from the measurement system characterization. There are overall six characterization measurements, each of which contributes to the correction factor. These measurements are discussed in detail in Refs. [21, 52, Publ. III]. One of the characterization measurements is particularly interesting, because it requires that the reflectivity of the inner surface of the sphere is spatially scanned. Instead of using a miniature incandescent lamp as a scanner light source, a novel design at the TKK incorporates a high-intensity LED with a small achromatic lens, making the scanner smaller and lighter [Publ. II, Publ III].

Tests with lamps having significantly different intensity distributions were conducted by the NIST and the PTB in order to evaluate the related measurement errors [56]. Since the additional uncertainty caused by the non-uniformity of the intensity distribution was found to be negligible, the characterization measurement to determine the spatial correction for the lamp inside the sphere can be accounted for by a corresponding uncertainty component of the correction factor of unity. If extreme accuracy is required, the spatial intensity distribution of the lamp can be measured using goniophotometric methods.

The characterizations are time-consuming, but the actual luminous-flux measurement is fast and reliable. With optimized measurement procedure, the measurement time of one lamp is reduced to 15 minutes, including the lamp stabilization time of 10 minutes.

Expanded uncertainty for the unit of luminous flux is estimated to be 0.47 % [Publ. III], which is among the lowest values reported in the world. The validity of the uncertainty estimate has been tested by international comparisons and test measurements with NIST (USA) and SP (Sweden) [Publ III, Publ. IV].

3. International intercomparisons

Each NMI develops new and maintains existing units of measurement. Since there is no such thing as "absolute truth", the measurement results always include some uncertainty. The only way to verify that the given uncertainty is correct is to compare results of measurements of lamps or detectors with other NMIs. Largest photometric and radiometric comparisons are world-wide key comparisons initiated by the CCPR. Most common international intercomparisons are small, having two or three participating NMIs. TKK has taken part in a number of large and small photometric and radiometric comparisons [22, 48, 57, 58, Publ. III, Publ. IV]. As a proof of success in these comparisons, all quantities maintained by the TKK have been accepted, with claimed uncertainties, to the CMC database of the BIPM [46].

3.1. Illuminance responsivity comparison with NIST (USA)

The illuminance responsivity scales were compared at TKK in 2000 using the 4.5-m optical bench with accurate length scale and stable light source (Osram Wi41/G) operated at the correlated color temperature of 2856 K. The illuminance values were measured with two NIST photometers (LMT P15 FOT, calibrated for illuminance responsivity before and after the transportation to Finland), and TKK reference photometer with distances of 2.085, 2.585 and 3.085 m from the lamp. The photocurrents were amplified with a current-to-voltage converter and recorded using a digital voltage meter. The relative expanded uncertainties of the NIST and TKK illuminance units were 0.39 % and 0.18 %, respectively [15, 17]. Taking into account the short-term drifts of the photometers and the uncertainty components related to the comparison measurements, the relative expanded uncertainty of the agreement of the units was estimated to be 0.47 % [Publ. IV]. The difference between the measured illuminance responsivities was well within the uncertainty, being only 0.08 % on the average [Publ. IV]. Such small difference and measurement uncertainty show that the measurement capabilities at the TKK are excellent in the field of photometry.

3.2. Luminous flux comparison with NIST (USA)

After the illuminance responsivity comparison, the luminous flux units were compared using the TKK 1.65-m absolute integrating sphere set-up described in Figure 2. Traceability from the unit of luminous intensity came via a commercial standard photometer (PRC TH15) calibrated with the reference photometer during the illuminance responsivity comparison. Four NIST luminous flux standard lamps (Osram Wi40/G GLOBE, calibrated for luminous flux before and after the transportation to Finland) were measured twice, on consecutive days, and the results were averaged. At the time of the comparison, the relative expanded uncertainties of the units of luminous flux at the NIST and the TKK were 0.62 % and 0.78 %, respectively. Taking into account additional uncertainty components (calibration and stability of the transfer lamps, calibration of NIST lamps at TKK) the relative expanded uncertainty of the agreement of the units was estimated to be 1.01 % [Publ. IV]. The average difference of the measured luminous flux values for four lamps was only 0.06 % [Publ. IV]. For a completely new realization of a unit this is a remarkable result, indicating the good quality of photometric research at the TKK.

3.3. Luminous flux comparison with SP (Sweden)

The luminous flux unit maintained at the TKK was compared again in 2003. By then, the measurement set-up was already completed with a new lamp holder [Publ. III] and revised relative expanded uncertainty estimate of 0.47 % was established. Two luminous flux standard lamps (GEC Hirst) from SP (Sweden) were measured using the TKK integrating sphere. The lamps had been calibrated by BIPM in 2001 with a relative expanded uncertainty of 1.0 %. The relative expanded uncertainty of the agreement of units including the measurement related uncertainty components was estimated to be 1.10 %. The average difference of the measured luminous flux values between TKK and BIPM was 0.16 % [Publ. III] indicating a very good agreement between these units and giving further confidence for the claimed uncertainty of the TKK luminous flux unit.

4. Light-emitting diodes and challenges in photometer calibration

In the early years of photometry, the light was emitted by flames and glowing filaments [2] having continuous spectral distributions for which straightforward measurement methods can be applied. Problems began to appear after the first commercial fluorescent lamp was developed in the late 1930’s and patented in 1941 [59]. Discharge lamps became more and more popular in general lighting applications because of their lower power consumption and longer life-time as compared to incandescent lamps. Concerning the field of photometry, however, they had a major drawback: the light spectrum was not only continuous but it also had spectral lines. A photometer calibrated with an incandescent lamp would give erroneous results for these kinds of lamps; errors up to several per cent would be obtained depending on the spectrum of the discharge lamp and the quality of the $V(\lambda)$ filter. Even worse problems may appear with the new LED light sources.

4.1. LED properties and correction for spectral mismatch

A single LED does not emit much light and to increase the luminous intensity of an LED, the light is often restricted to a small solid angle with an integrated lens. For applications where large intensities, comparable to those achieved by incandescent lamps are needed, a cluster of LEDs with external lenses or reflectors can be used. However, these kinds of light sources are far from standard lamps traditionally used as light sources in photometric measurements. Large LED clusters do not even behave as point sources anymore, making measurement geometries more challenging and application of fundamental optical radiation laws much harder.

Unlike incandescent and discharge lamps, LEDs are quasi-monochromatic light sources. The emission spectrum of a single-color LED is similar to monochromatic laser radiation, but widened. The width of the spectrum between the wavelengths where the intensity has dropped by 50 % from the peak value is a measure of the monochromaticity of the light and commonly referred to as full width at half maximum (FWHM). With single-color LEDs the FWHM –values are typically between 20-50 nm which makes the quality of the $V(\lambda)$ filter within that particular spectral region a key issue. White LEDs are a bit easier to measure, because they emit light throughout the visible wavelength region. With LEDs, white light is quite easily achieved by adding yellow phosphor to a blue LED that has peak emission wavelength around 470 nm [60]. The blue light excites the phosphor which emits broadband radiation in the yellow wavelength region. Mixing of the blue and the yellow color produces "blueish" white.

Figure 3 shows the spectral power distributions of four LEDs of different color accompanied with the spectrum of the CIE standard illuminant A and the $V(\lambda)$ curve. It can be seen that, e.g. with the red LED, a photometer with a $V(\lambda)$ filter having a small deviation from the theoretical $V(\lambda)$ curve around 630 nm relative to its peak value may result in a large measurement error.

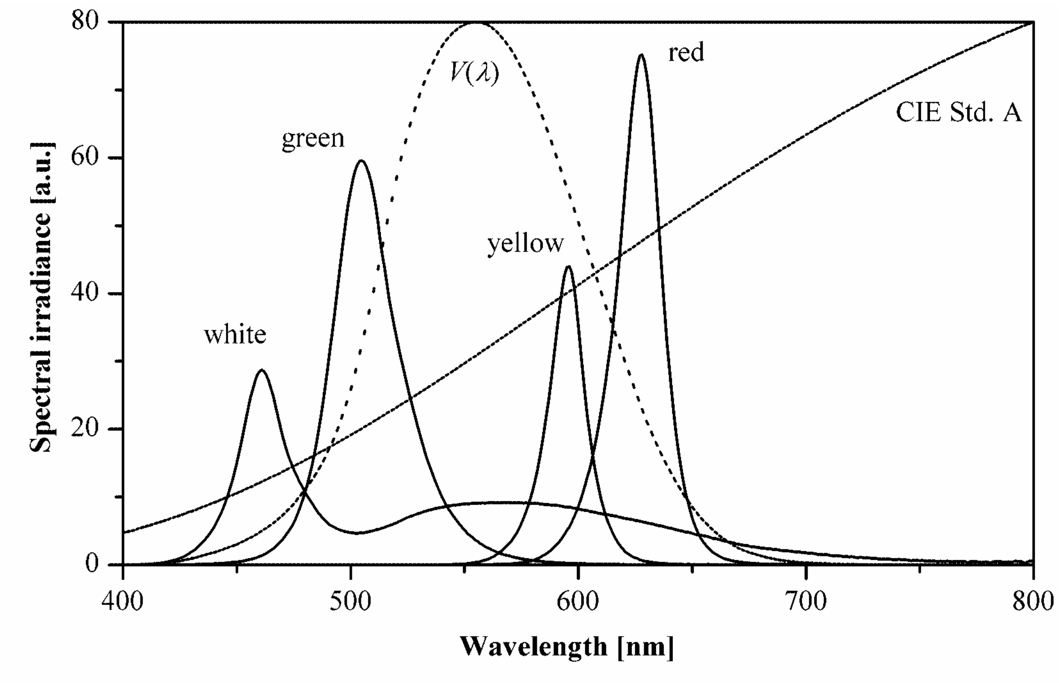

Figure 3. Spectral power distributions of four LEDs shown with the $V(\lambda)$ curve and the spectrum of the CIE standard illuminant A.

Correction can be applied if the relative spectral responsivity of the photometer and the relative spectral power distribution of the light source are known. A spectral mismatch correction factor F for the photometer can be calculated [61] as

$$F = \frac{\int S_{\mathrm{A}}(\lambda) s_{\mathrm{rel}}(\lambda) \mathrm{d}\lambda}{\int S_{\mathrm{A}}(\lambda) V(\lambda) \mathrm{d}\lambda} \frac{\int S_{\mathrm{t}}(\lambda) V(\lambda) \mathrm{d}\lambda}{\int S_{\mathrm{t}}(\lambda) s_{\mathrm{rel}}(\lambda) \mathrm{d}\lambda}, \tag{8}$$

where $S_{\mathrm{A}}(\lambda)$ is the relative spectral power distribution of the CIE standard illuminant A used for the absolute calibration, $S_{\mathrm{t}}(\lambda)$ is the relative spectral power distribution of the source to be measured and $s_{\mathrm{rel}}(\lambda)$ is the relative spectral responsivity of the photometer.

Despite the obvious drawbacks concerning the properties of LEDs, they do have many advantages: they are nowadays widely used in applications where low energy consumption, robust structure and long maintenance interval are important. One such application is a maritime beacon either on a floating device at the sea or on a fixed structure at the harbor.

4.2. Photometer calibration methods

The recommendations on various aspects concerning maritime navigation, including photometry of signal lights, are given by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA). The LED buoy lantern used as a signaling beacon should have the right color with adequate and horizontally uniform luminous intensity. The IALA recommends two alternative methods for photometer calibration when LED sources are measured [62]. A commercial photometer used for on-line testing of manufactured LED lanterns was calibrated at TKK with both methods following IALA guidelines [Publ. V].

4.2.1. Calibration using incandescent light source

The commercial photometer (later referred as photometer) was calibrated for illuminance responsivity with the TKK reference photometer using a luminous intensity standard lamp (operated at 2856 K) as a light source.

Since the spectra of the LED lanterns were different from the spectrum of the lamp used for absolute calibration, the spectral mismatch correction factors were calculated for the photometer. For this purpose, the relative spectral responsivity of the photometer was measured with the TKK reference spectrophotometer

[63, 64]. Additionally, the relative spectral power distributions of the lanterns were required. They were measured with a calibrated spectroradiometer and are those presented in Figure 3.

The final correction factors for the photometer, one for each lantern, were obtained by multiplying the corresponding spectral mismatch correction factors with the correction factor from the absolute illuminance responsivity calibration.

4.2.2. Calibration using LED-based light source

Instead of using a standard lamp, the photometer was calibrated with the TKK reference photometer using the four LED lanterns as light sources. The relative spectral power distributions of the lanterns were needed to calculate the spectral mismatch correction factors for the reference photometer whose relative spectral responsivity was already known and presented in Figure 4.

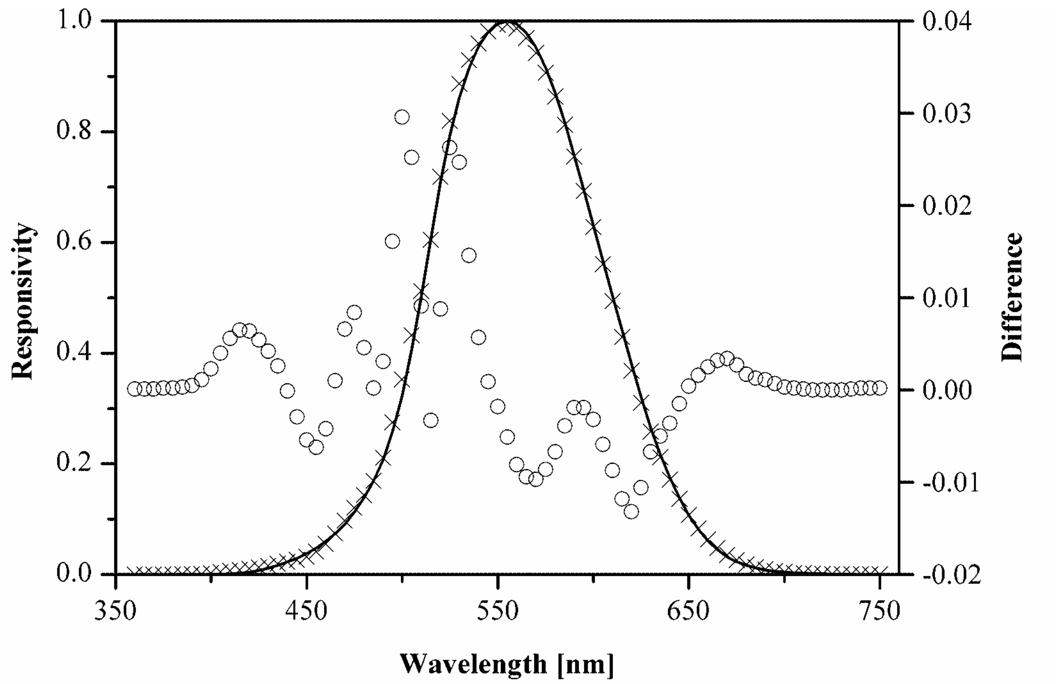

Figure 4. Relative spectral responsivity of the reference photometer (crosses) as compared with the $V(\lambda)$ curve (solid line). Open circles represent the difference between the two curves.

The final correction factors for the photometer were obtained by dividing the color-corrected illuminance values measured by the TKK reference photometer with the illuminance values measured by the photometer.

4.3. Evaluation of the calibration methods

Although problems with light sources that have either narrow spectra or are spatially limited were of general knowledge in the field of photometry, to my knowledge this was the first time when a thorough investigation of different photometer calibration methods has been reported in the literature [Publ. V].

The differences between the correction factors for white, green, red and yellow lanterns were 0.002, 0.006, -0.010 and 0.004, respectively. The consistency between the correction factors obtained with different methods was good and within uncertainties (relative expanded uncertainties were 0.9 % and 1.0 %) [Publ. V]. Surprisingly, the lantern with red LEDs had negative difference due to a larger correction factor with the latter calibration method. Further studies with that particular lantern included measurements of vertical spatial intensity with three different lateral angles. It was found out that the optical and mechanical axes were not always the same. This leads to problems with photometers which have apertures of different sizes. When such photometers measure a narrow intensity peak, there will inevitably be differences in measured illuminance values, because the photometers measure different amounts of light. This does not occur with standard lamps, which act as point sources and have uniform far-field intensity distributions.

Since both calibration methods gave similar results, further evaluation was based on more practical matters. The spectral power distributions of the LED lanterns are measured in any case to obtain spectral mismatch correction factors for the photometers. The first method (with a standard lamp as a light source) is more laborious because of the relative measurement of the spectral responsivity of the commercial photometer. The absolute level of the calibration is achieved with a standard lamp which is a reliable and easy light source to use. If LEDs with new colors are taken into use, only their relative spectral power distributions need to be measured to calculate new spectral mismatch correction factors. The second calibration method is simpler and the time required for the calibration is relatively short, but in the situation described above, both the lantern and the photometer would have to be brought for calibration. In addition, a light source based on LEDs was found not to be a very good standard source due to the spectral and spatial properties.

As a conclusion of the evaluation process, the first calibration method was eventually considered to be a better choice. It does require more measurements when the photometer is calibrated for the first time, but the absolute illuminance responsivity measurement is more reliable in every way. Future upgrades that may include implementation of completely new LED colors or modification of existing colors with slightly different spectra are easier because only the spectra of the LED lanterns need to be measured. Also the maintenance of the absolute measurement level is easy due to the accurate and reliable illuminance responsivity calibration with a standard lamp.

5. Calibration errors caused by diffusers

Commercial photometers (also called as luxmeters, because they measure illuminance whose unit is ‘lux’) are manufactured by various companies and widely used in lighting design, photography, occupational health care and corresponding applications. The luxmeters have large measuring ranges (> 200 000 lx) and reasonable accuracies of a few per cent, depending on the type of the silicon photodiode detector and the quality of the filter in front of it.

The professional photometers used by the NMIs usually have open apertures which limit the measurement solid angle and define precisely the distance reference plane of the photometer. A luxmeter, however, is often equipped with a white diffuser in front of the detector-filter package to improve the angular responsivity (cosine response) and to widen the measurement solid angle. Diffuser material is usually white plastic or opal glass. This thesis includes the first reported study [Publ. VI] in the world to systematically determine the magnitude of the measurement error caused by the diffuser.

5.1. Displacement of the distance reference plane of the diffuser

In order to improve the cosine response, the commercial luxmeters usually have dome-shaped diffusers. For special purposes other shapes, such as cylindrical diffusers, are also available. The cost for the improved cosine response is the shift of the distance reference plane to an unknown location [35]. This leads to errors in illuminance responsivity calibrations, where for simplicity the reference plane is typically assumed to be at the outermost surface of the diffuser. Let us consider a situation where the distance reference plane is 5 mm inside the diffuser and the calibration takes place at a distance of 500 mm from the lamp having luminous intensity of 300 cd. The reference illuminance measured at 500 mm is 1200 lx. The photometer under calibration measures illuminance of 1176 lx at the distance of 505 mm introducing a systematic error of 2 % in the calibration.

5.2. Inverse-square law and the lamp reference plane

The first step was to make sure that the effective position of the lamp filament can be reliably measured, because otherwise the distance offset measurements would be meaningless. The standard lamp was operated several times and the illuminance was measured at different distances from the reference plane of the lamp (front surface of a removable alignment mirror in front of the lamp) with the reference photometer and three standard photometers equipped with 8-mm open apertures (HUT-1 and HUT-2) and a planar Teflon® diffuser of the same size (LM-1) [Publ. VI]. The luminous intensity of the lamp was determined by applying the inverse square law to the measured illuminance values according to equation

$$E_v = I_v \big/ \left(d + \Delta d_\mathrm{S} + \Delta d_\mathrm{P}\right)^2 , \tag{9}$$

where E_v is the measured illuminance, I_v is the luminous intensity of the lamp, d is the distance between the selected reference planes of the source and the photometer, Δd_S is the distance offset of the source, and Δd_P is the distance offset of the photometer.

The reference photometer had a known distance reference (aperture) plane and therefore Δd_P was zero. Using the least-squares method, fitting parameters Δd_S and I_v were determined. The distance offset of the source was measured 17 times with variable combinations of photometers and found to be quite repeatable, being on the average 79.6 mm behind the alignment mirror and having a standard deviation of 0.4 mm. Values measured with standard photometers were in good agreement, indicating that even the planar diffuser had zero distance offset. However, deviations up to 1.4 mm for Δd_S were measured with the same photometer. It is possible that the filament moves between consecutive lamp burns. For this reason it was decided to re-measure Δd_S every time the lamp was operated.

5.3. Diffuser reference planes

The magnitude of the displacement of the distance reference plane, or distance offset of the photometer Δd_P, was studied on an optical bench. Two commercial luxmeters equipped with three different diffusers were compared with a standard photometer to find out how large errors in calibration the diffusers inflict. The luxmeters were compared with a standard photometer (HUT-2) having an open aperture. The images and schematic drawings of the diffusers are presented in Figure 5. Dimensions of the diffusers in the drawings are presented in Table 1.

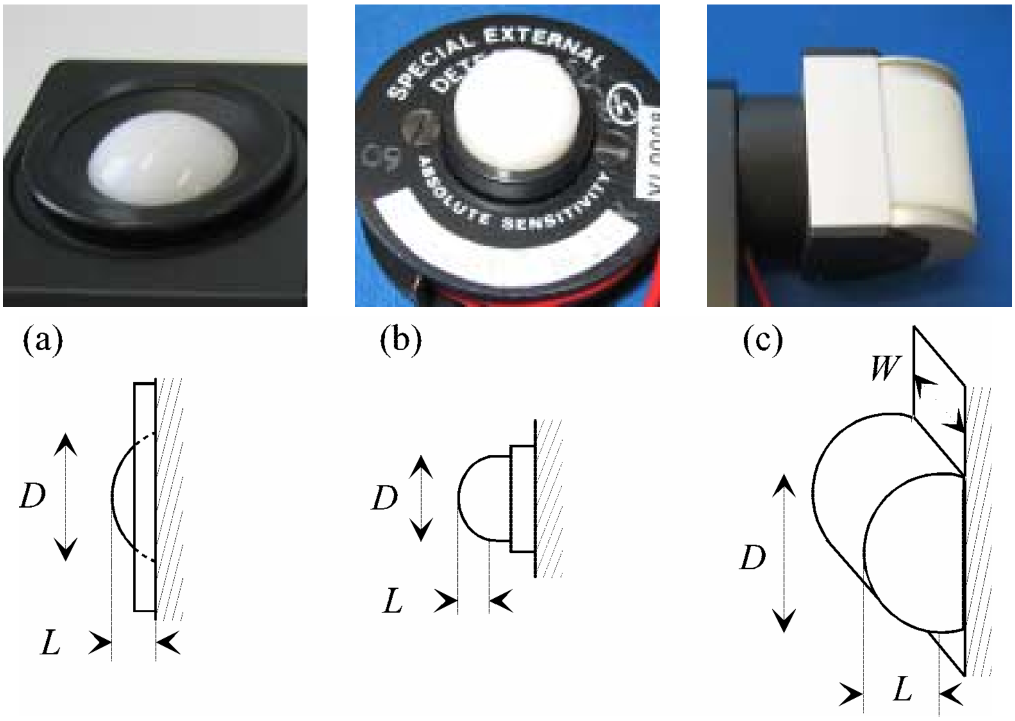

Figure 5. Images and schematic drawings of the investigated diffusers.

Illuminance values were measured at six distances (500 - 1500 mm) from the front surface of the alignment mirror. Data analysis was carried out for each detector using Eq. (9). The least-squares fitting was done by varying the parameter $\Delta d_S + \Delta d_P$, which includes the distance offsets for both the detectors and the lamp. Distance offset Δd_P for HUT-2 was known to be zero from the previous measurements with the reference photometer. Therefore the lamp offset Δd_S can be accounted for by subtracting the results for HUT-2 from the results for the tested photometers. The obtained distance offsets are presented in Table 1.

Table 1. Measured distance offsets Δd_P of the reference planes of the diffusers. Diffusers are denoted as in Figure 5. Uncertainties are calculated as the standard deviations of the mean from 3-4 measurements for each diffuser.

Diffuser		(a)	(b)	(c)
Dimensions [mm]	D	24.3	16.0	30.0
	L	8.0	7.1	15.0
	W	-	-	26.1
Offset Δd_P (mm)		5.0 ± 0.5	7.8 ± 0.3	8.5 ± 0.7

It was also found interesting to investigate, whether it is possible to derive the distance offset from the physical dimensions of the diffuser or not. Assuming that each infinitesimal surface element of the diffuser contributes to the photometer signal an amount proportional to the cross-sectional area of that element and its illuminance, a mathematical model can be applied based on the shape of the diffuser [Publ. VI]. However, the results showed clearly that the distance offsets have to be measured; they can not be determined from the geometrical measures of the diffusers. The calculated offsets were several millimeters smaller than the measured ones, indicating that the measured distance offset is likely to be affected by the diffuser material, together with both the internal and the external structure of the photometer head.

5.4. Correction for erroneous illuminance responsivity calibration

In all three diffusers, the reference plane according to which the inverse square law holds was found to be several millimeters behind the outermost surface of the diffuser. This is a very significant finding, because at short distances the distance offsets cause severe problems: at the distance of 500 mm the errors in illuminance responsivity calibrations for diffusers (a)-(c) with the distance offsets presented in Table 1 are 2.0 %, 3.1 % and 3.4 %, respectively. All these values exceed the typical 1.0 % uncertainty for routine illuminance responsivity calibrations at the TKK.

When the distance reference planes have been determined, the erroneous measurement results can be very easily corrected. The standard photometer providing the reference value can be virtually moved to the reference plane of the diffuser and new reference illuminance value, based on the inverse square law, can be calculated and compared to the reading of the luxmeter. This way, systematic errors of 2.0 % in photometer calibration can be reduced to statistical variations of the order of 0.2 % [Publ. VI].

From the international point of view, the importance of these results for the field of photometry is obvious. Such a study that shows how serious the problem is and in how straightforward way it can be accounted for has not been reported before. There is no doubt that NMIs worldwide will have to pay attention to this matter

6. Conclusions

In this thesis, new national measurement standards for the realizations of the units of luminance, spectral radiance and luminous flux are presented. All the realizations are based on characterized detectors.

The realizations of the units of luminance and spectral radiance are based on the integrating sphere light source, the reference photometer and the spectroradiometer. The measuring ranges of luminance and spectral radiance are 250 – 40000 $cd \cdot m^{-2}$ and 0.0001 – 1 $W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}$, respectively.

The realization of the unit of luminous flux is based on the absolute integrating sphere method, utilizing a 1.65-m integrating sphere, two photometers and an external light source. The measurement facility at the TKK is one of the two permanent and operational installations of this kind in the world. The measuring range of luminous flux is 10 – 10000 lm.

The uncertainty analyses are carried out for the realized units. The relative expanded uncertainties for the unit of luminance and luminous flux are 0.36 % and 0.47 %, respectively. The uncertainty of spectral radiance is wavelength dependent and presented in [Publ. I]. The claimed relative expanded uncertainty of luminous flux is one of the lowest values ever reported, and its validity has been verified by international intercomparison measurements with the NIST (USA) and the SP (Sweden). All measurement capabilities presented in this thesis have been peer reviewed and accepted to the CMC database maintained by the BIPM.

The semiconductor technology advances rapidly and the solid-state lighting becomes more common and cost-efficient. This brings challenges for the modern photometry, because the spectral and spatial properties of light-emitting diodes are completely different from those of incandescent lamps. In order to gain further knowledge of the photometry with LED-based light sources, the TKK made collaboration with Sabik Oy, a company which produces maritime light-emitting diode buoy lanterns. In the resulting publication, which still seems to be the only one in the world where this subject is thoroughly discussed, the TKK evaluated two methods to calibrate a commercial photometer that measures LED sources. Deeper understanding of the problems and advantages in photometry concerning LED sources gives Sabik Oy competitive advantage in the worldwide markets of maritime signaling devices.

Commercial luxmeters usually have dome-shaped or cylindrical diffusers to improve their angular responsivity. The TKK was the first NMI in the world to publish a scientific article that brought up the huge errors the diffusers may cause in illuminance responsivity calibrations. A correction method based on the inverse square law was developed for the luxmeter calibrations, reducing the systematic errors of several per cent to small random variations. Even though the problem and the solution are based on the very basics of photometry, it was a pleasure to see that important and significant issues still exist even on the basic level and that they can be investigated without tremendous financial investments on measuring equipment. This finding will inevitably raise discussion about the illuminance responsivity calibration procedures of the NMIs, possibly even changing them. Meanwhile, the TKK has extended this research to spectroradiometry, where the diffuser-induced errors in irradiance responsivity calibrations may have equally significant effects in global solar UV measurements.

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