Aalto University
School of Electrical Engineering
Metrology Research Institute

Jari Hovila
Pasi Manninen
Tuomas Poikonen
Janne Askola
Tomi Pulli

Quality Manual of Luminous Flux Measurements

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1. Table of contents

2. Definition

2.1. Scope

This instruction manual describes the principle and the operation of the equipment used for detector-based luminous flux (lm) measurements. The calibrated devices are standard lamp light sources.

2.2. Object and field of application

Standard photometer: Secondary standard for illuminance measurements.

Sphere photometer: Measures illuminance levels relative to the luminous flux.

Spectroradiometer: Used for measuring the spectrum of the luminous flux sources.

Integrating sphere: Collects the total luminous flux of the lamp inside the sphere.

2.3. Features

a) Standard photometer:

See Ref. 1.

b) Sphere photometer:

Diffuser-equipped photometer attached to the integrating sphere. It measures illuminance values that are relative to the luminous flux levels inside the sphere.

c) Spectroradiometer:

See Ref. 2.

d) Integrating sphere:

The diameter of the sphere is 165 cm. The inner surface of the sphere is painted with a high-reflectance $BaSO_4$-coating. The sphere consists of two hemispheres which can be separated to mount/change the lamp inside.

2.4. Principle of the realization

The principle of the realization is described thoroughly in [3-5]. Therefore only a short introduction to the theory is given here.

The unknown luminous flux of a standard lamp (later referred as the internal source) inside the integrating sphere is measured by comparing it against a known reference luminous flux introduced to the sphere from an external source through an opening on the sphere wall.

The reference luminous flux is obtained by measuring the illuminance of the external source at the aperture plane of a precision aperture outside the sphere. The reference luminous flux is then

$$\Phi_{ext} = E_v A \,, \tag{1}$$

where E_v is the measured illuminance and A is the area of the aperture.

The standard photometer is removed and the reference luminous flux enters the sphere through a 10 cm opening. The signal y_{ext} from the sphere photometer is recorded. The external source is then switched off and the internal source is switched on. Another signal from the sphere photometer y_{int} is recorded. The luminous flux of the standard lamp inside the sphere can then be obtained as

$$\Phi_{int} = \frac{y_{int}}{y_{ext}} \Phi_{ext} \,. \tag{2}$$

The resulting luminous flux value is then multiplied by a correction factor f which consists of six sub-correction factors:

- Spectral-mismatch correction factor for the external source
- Spectral-mismatch correction factor for the internal source
- Correction factor for the spatial non-uniformity of the sphere surface
- Correction factor for the angular intensity distribution of the luminous flux standard lamp
- Correction factor for the non-uniformity of the illuminance at the aperture plane
- Correction factor for the different reflectivity of the sphere surface on different incident angles.

These correction factors are further explained in [4].

3. Equipment

3.1. Description of setup

3.1.1. Equipment needed for calibrating luminous flux standard lamps

Equipment needed in the luminous flux calibrations is presented in

Table **1**.

Table 1. Equipment of luminous flux calibrations.

Description		Quantity	Serial NR / Identification
A. Light measurement			
1.	PRC photometer [1]	2	HUT-1 / HUT-2, LM-1 / LM-2
2.	Integrating sphere	1	Labsphere LMS-650
3.	Spectroradiometer [2]	1	Bentham DTMc-300
4.	Precision aperture	3	AV1, AV2, AV3
5.	Current-to-voltage converter (CVC)	1	Lab Kinetics SP042, MRI CVC
6.	Digital voltmeter (DVM)	1	HP 3458A
B. Light source			
1.	Osram Sylvania T6	1	BN-9101-391, BN-9101-465
2.	Osram Wi40/G Globe	5	LMS9901-02, LMS0003-05
3.	Lamp power supply	2	Heinzinger PTN55 125-10
4.	Standard resistor	2	Guildline 9230-15 (0.1 Ω): s/n 65852 / 62587
5.	Digital voltmeter (DVM)	3	HP 3458A
6.	Alignment laser	1	OMTec
C. Control and data acquisition			
1.	Computer	1	PC with access to MIKES-Aalto file system.
2.	Software	1	Lumen_TKK.vi

3.2. Calibration requirements

3.2.1. Maintenance

To ensure accurate measurement results and traceability, the measurement system and the devices used in the calibrations must be calibrated regularly. The characterization of the measurement system is performed according to schedule presented in Table 2. The calibration schedule for the devices is presented in Table 3. The luminous flux standard lamps should be measured every 2 years, or at the same time with customer’s lamps to ensure stability of the luminous flux scale. The burning times should be minimized because of poor availability of new standard lamps.

Table 2. Schedule for the system characterization measurements.

Characterization component	Calibration interval
Sphere surface scan	4
Aperture plane illuminance distribution	4
Spectral throughput of the sphere	4
Incident angle	8

Lamp spectra	2

Table 3. Shedule for the device and lamp calibrations.

Device to be calibrated	Calibration interval
PRC photometer	1
Spectroradiometer	See [2]
Precision aperture	4
Current-to-voltage converter	See [6]
Digital voltmeter	See [6]
Precision resistor	See [6]
Temperature and humidity meter	See [6]
Luminous flux standard lamps	2

4. Measurement traceability

The unit of luminous flux is linked to the detector-based photometric scale of Metrology Research Institute via the illuminance responsivity of the standard photometer. Therefore, the luminous flux scale is traceable to the primary standards of optical power, spectral transmittance and length. The traceability chain of the unit of luminous flux is presented in Figure 1.

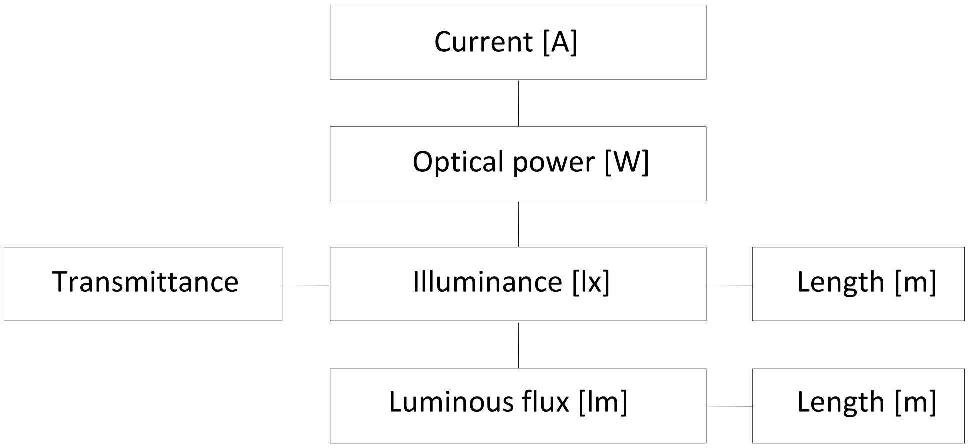

Figure 1. Traceability chain of the unit of luminous flux.

4.1. Uncertainty budget

The uncertainty budget of luminous flux calibrations is presented in Table 4. More detailed information about the uncertainty budget can be found in [4].

Table 4. Uncertainty budget of luminous flux calibrations.

Source of uncertainty	Relative standard uncertainty [%]
System characterization and calibration	
Spatial correction factor scf_e	0.05
Spatial correction factor scf_i	0.03
Ratio of colour correction factors ccf_e / ccf_i	0.02
Correction for incident angle dependence β	0.05
Correction for illuminance non-uniformity k_a	0.03
Unit of illuminance	0.15
Transfer to standard photometer	0.10
Drift of the standard photometer	0.04
Photometer distance	0.10
Aperture area	0.01
Stray light	0.01
Drift of the reference lamp	0.01
Noise (illuminance)	0.03
Noise (reference flux)	0.02
Current measurement (illuminance)	0.01
Current measurement((reference flux)	0.05
Luminous flux measurement	
Non-linearity of the sphere photometer	0.01
Temperature increase	0.01
Noise	0.01
Current measurement	0.01
Other	
Sphere opening / closing	0.01
Repeatability (typical)	0.05
Lamp holder	0.10
Combined standard uncertainty	0.26
Expanded uncertainty (k = 2)	0.52

5. Calibration and measurement procedures including validation methods

The luminous flux measurement setup is presented in Figure 2. The figure is simplified; it does not contain power supplies, precision resistors, DVMs, CVC nor wirings. The reference luminous flux is produced using the stable external source of type 1000 W Osram FEL Sylvania T6, aperture array with a shutter, precision aperture and a standard photometer. As a standard photometer, HUT-1 or HUT-2 is used. The photometer used in the detector port of the sphere is either LM-1 or LM-2 with diffuser input. A spectroradiometer can be mounted to the detector port of the sphere using a diffuser-adapter. Spectral measurements are needed for determining the spectral-mismatch correction, and the CCT of the lamp, as well as the spectral throughput of the sphere.

The sphere is equipped with three baffles that are coated using the same $BaSO_4$ painted, as the sphere. Any light illuminating a baffle gets diffuse-reflected from its surface. The purpose of baffle 1 is to prevent the flux test-lamp from escaping the sphere through the opening used for the reference flux during the measurements. Baffle 2 ensures that the detector does not see the test-lamp directly, but only the light optically integrated by the sphere surface. The auxiliary lamp and baffle 3 form an additional source that can be used for self-absorption measurements of test-lamps. The auxiliary lamp is not used in calibrations, where the external source is operated. The self-absorption of the luminous flux standard lamp is taken into account in the luminous flux responsivity calibration of the system.

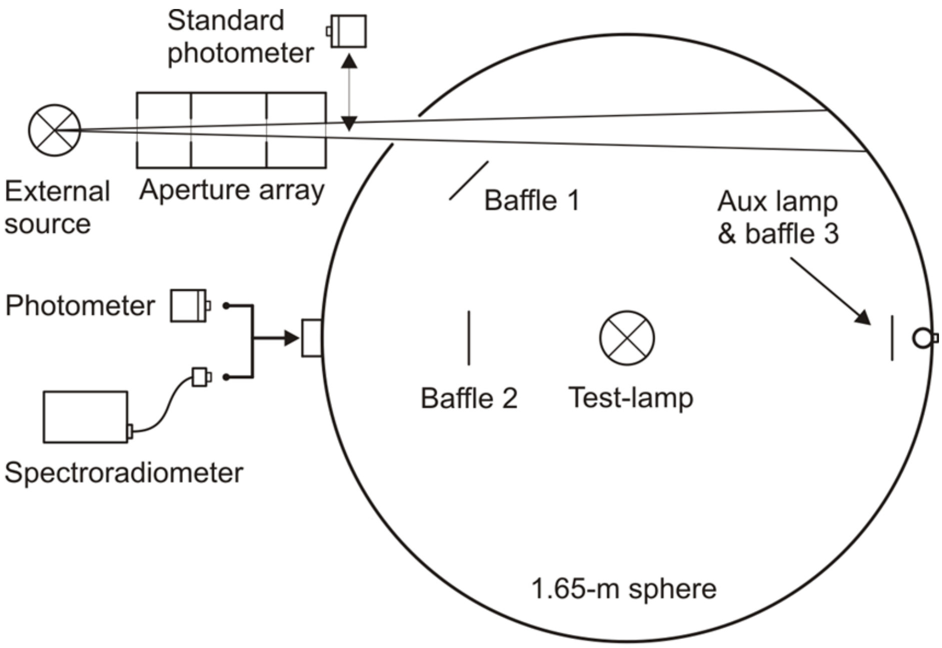

Figure 2. Luminous flux measurement setup.

5.1. Wirings

Wiring of the external source is described in [7]. DVM-2 (front terminal) is used for the internal lamp current measurement. The lamp holder for the internal source is attached to the top of the sphere. The lamp is mounted base up and so that the filament of the lamp is at the center of the sphere. The lamp mounting base has a 4-point E27 socket for precise operating current and base voltage measurements. DVM-2 (rear terminal) is used for the current measurement of the external lamp. In a similar way, the DVM-3 is used for the voltage measurement of both internal (front terminal) and external (rear terminal) lamps. The measurement can be conducted using one or two CVC devices. If two CVCs are used, both photometers can be connected at all times and the photometer, of which signal is to be measured is selected using the front/rear terminal switch of the DVM-1. If only one CVC is used, the signal cables from the photometers are manually switched using the adapter box of the LM-1 photometer.

5.2. Measurement procedure

The measurement program **Lumen_TKK.vi** is located in the measurement computer in directory

\\work.org.aalto.fi\T405\MIKES-Aalto\Quality\Photom\Software

The program gives instructions about necessary actions (eg. wiring changes) between different calibration phases.

The following measurement procedure is different than described in Chapter 2.4, but it is optimized to fulfil the following criteria:

- The operating time of the internal source remains minimum
- Overall time of the calibration is minimized
- Several internal sources can be consecutively measured (external source is not switched off at any point)
- No unnecessary wiring changes

Normally the aperture AV2 with a nominal diameter of 40 mm is used. The external source is operated at a colour temperature close to that of the standard illuminant A (2856 K). The operating currents of the luminous flux standard lamps of the Metrology Research Institute are chosen so that their correlated colour temperature is close to 2750 K.

The current of the internal source must be set as close as possible to the nominal value because the current has a direct effect on the obtained luminous flux value. Two Heinzinger PTN55 125-10 power supplies equipped with output current fine-tuning are used for operating the internal and external source during the measurements.

Procedure for luminous flux standard lamp calibration:

1. External source is switched on
2. Aperture array shutter is closed
3. After 30 minutes, internal source is switched on
4. After 10 minutes, signal from LM-1 is measured
5. Internal source is switched off
6. The dark current of LM-1 is measured with two different CVC sensitivity levels
7. HUT-1 is put in place and its dark current is measured
8. Aperture array shutter is opened
9. Signal from HUT-2 is measured
10. HUT-1 is removed, signal from LM-1 is measured
11. Aperture array shutter is closed
12. Internal source is changed and switched on
13. Calibration is continued from step 4.

The measurement data is analyzed using a LabVIEW-file **Lumen_TKK.vi**. It is located in the measurement computer, in directory

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The dark currents are automatically subtracted from the photocurrents. The calculated luminous flux of the internal source is adjusted by multiplying it with a valid correction factor f. The luminous flux is further adjusted by comparing the recorded operating current and base voltage against the nominal values.

5.3. Characterization procedure of the measurement system

The characterization results as well as the relevant details of the measurement setups – e.g., the instruments used in the measurements – should be stored in directory

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5.3.1. Measurement of illuminance distribution on the aperture plane

The illuminance distribution of the external lamp (FEL-465) is measured on an optical rail. Two linear translators are assembled as XY-configuration for moving the HUT-1 or HUT-2 photometer head within the area corresponding to the 40-mm precision aperture used in the measurement of reference luminous flux see Figure 3. The aperture is not used in this measurement. The distance between the lamp and the photometer should be the same as in the reference luminous flux measurement, i.e. 700 mm.

The alignment of the XY-translator is carried out with the two-beam alignment laser and a mirror pressed against the adapter plate of the vertical translator. The construction of the translator needs to be fine-tuned to obtain movement that is perpendicular to the optical axis. After this, the photometer can be attached to the vertical translator, and aligned using the two-beam alignment laser. During the alignment, the translators need to be near their mid positions that there is enough travel left to cover the whole aperture area. The photometer can be mounted to the translators using a right-angle plate, kinematic mount and optical posts, as shown in Figure 3.

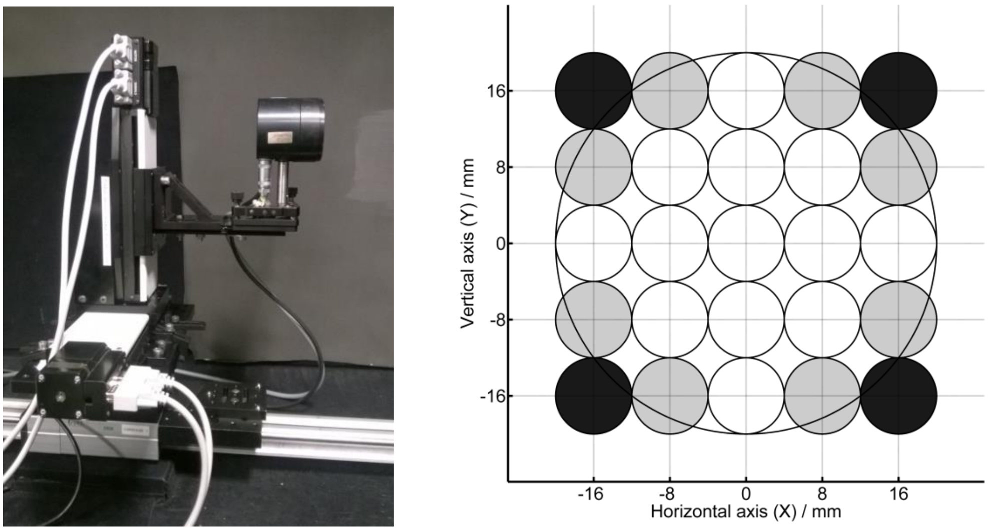

Figure 3. HUT-2 photometer assembled on two linear translators for illuminance uniformity measurement (left) and the pattern used in the measurement (right).

The linear translators used in the measurement are of type Newmark NLS4-4 and NLS4-6 with travels of 100 mm and 150 mm, respectively. Two NLS4-6 translators could also be used. The translators are driven with a Newmark NSC-A2L motion controller, which uses Performax-drivers on PC-side. The measurement programs and Matlab-functions needed for the measurement can be found in the directory

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In the FEL_spatial_scan.vi, the photometer should first be moved to optical axis manually using the program functions. After pressing the "Measure"-button, the program measures the lamp signal for 60 seconds at the optical axis (middle point). Of these 60 seconds e.g. first 20 seconds can be used for measuring the dark current by manually controlling the shutter. Then, a sequence of ten different scans is initiated. In each round the illuminance distribution of the lamp is scanned using the 5x5 –grid shown in Figure 3. The diameter of the measurement sites is 8 mm and corresponds to the diameter of the standard photometer aperture. The illuminance at the optical axis (middle point) is measured for 10 seconds between the rounds for monitoring the stability of the lamp and the measurement system. After the sequence, the photometer is returned to the optical axis by the program. The program saves the date and starting time of the measurement together with the text in the comments-field and the measurement data.

The measurement data is analyzed with FEL_spatial.m Matlab-function. In this function the measurement file should be put correctly in the given variable and nothing else should be changed. The function calculates the illuminance distribution correction factor for each measurement round described earlier and returns the mean and standard error of these values. Returned standard error is presented as a percentage of the mean. The measurement points shown in Figure 3 with grey face colour are weighted with the area that lies inside the 40 mm of the precision aperture. Measurement points with black colour are discarded. The weighting factor is calculated geometrically when the diameters of the precision aperture and reference photometer aperture are known. For the values 40 mm and 8 mm, respectively, the weighting factor is 0.8056.

5.3.2. Scanning of the spatial uniformity of the integrating sphere

Due to small spatial differences in the coating reflectivity of integrating spheres, as well as elements such as the baffles and the seam of the sphere, the sphere surface needs to be scanned with narrow beam source. This measurement is then used for calculating a correction factor for the case when light is input to the sphere at the reference port versus a lamp illuminating the sphere surface from inside. The scan is performed with 5° steps in sphere coordinates using a Czibula & Grundmann sphere scanner with a white LED (Figure 4). The measurement programs and Matlab-functions used in the measurements can be found in the directory

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Figure 4. Czibula & Grundmann Sphere scanner, the control unit and the cable to connect them to each other.

5.3.2.1 Preparations for the measurements

The scanner should never be rotated by hand!

Attach the sphere scanner firmly into the E27-socket of the integrating sphere. It is possible to use either one of the E27-base lamp holders for this measurements, but due to the dimensions of the scanner it is preferred to use the shorter holder meant for measurements of DC-operated luminous flux standard lamps.

Connect the control unit with the scanner cable to the two wires coming from the sphere. Be sure that the polarity is correct (brown cable with red connector to the ring and white cable with black connector to the tip of the E27-base). Connect the control unit to the measurement computer using a serial cable and a USB-to-Serial adapter. Ensure that the serial port for the scanner is correct in the software. Run the SScan.vi program. If the controls for moving the scanner are disabled, run the “Referenz” -function. This initialises the scanner and defines the rotating limits of the scanner motors. Switch on the scanner LED, and set the current value to 700 mA from the software. This is the maximum current that can be used. Leave the LED on and allow it to stabilize for at least 20 minutes. You can monitor the stabilisation of the source using a photometer.

Attach the LM-1 or LM-2 photometer to the detector port of the sphere and connect it to the power supply of its temperature controller and switch it on. Connect the photometer signal cable to a CVC, and the output of the CVC to a HP 3458A DVM. Check the settings of the measurement. The sensitivity of the CVC should be 10^7. Note that the instruments should be turned on for at least half an hour before starting the measurement in order to avoid errors due to stabilization.

5.3.2.2 Sphere scanning software

To begin the scan, target the scanner beam to the reference port baffle inside the sphere using the MOVE H/V controls in the software. The horizontal value should be a multiple of 5° and the vertical value can be given with 0.1° precision. Normally the value for the vertical angle is between 0° and 15° and between 250° and 270° for the horizontal. These might depend on the holder used in the sphere. After this, close the sphere firmly from the direction of the auxiliary port.

Check the GPIB address for the DVM, and select the save location for the measurement file. Insert values for time to wait before the first measurement in seconds, step size (typical value: 5°), standard deviation threshold (0.01 %) and the integration time in number of power line cycles (10) for a single measurement point. If dark current measurement for the sphere is needed, turn the “DARK”-control on, this will turn the LED off and measure 100 points at 5 second intervals after the scanning sequence.

The measurement can be started by pressing the “Measure”-control. Measurement takes normally around four hours, but the cycle can be aborted by pressing the “STOP MEAS” control. At every measurement point, the mean of three consecutive readings that have standard deviation below the assigned threshold is saved to the measurement file with the standard deviation and the scanner position. Measurement values can be monitored from the measurement array. After the measurement sequence has ended, move the horizontal axis to 180° and vertical to 90°. At this point the program can be stopped by pressing the large red STOP-control.

To measure the self-absorption of the sphere scanner, leave the scanner attached to the holder with the LED turned off, and connect the 150-W auxiliary lamp to the Heinzinger PTN55 125-10 power supply. Drive the auxiliary lamp with a driving current of about 6 A. Initialize the setup using the same method as for the previous scan, preferably using the same values. Target the scanner beam again to the reference port using the values of the first measurement. Close the sphere and leave the auxiliary lamp and the temperature of the sphere to stabilize for 2-3 hours. After this, begin the scanning sequence with the SScan.vi –program. The program asks you to confirm that you really want to run the sequence without the scanner LED switched on. After the sequence, rotate the scanner to the horizontal angle of 90 ° and vertical angle of 180 °. Then, stop the program and remove the scanner from the sphere. Close the sphere and let the lamp to stabilize for an hour. After this, run the program SphereAUX.vi with the same settings as the previous scan using 50 to 200 rounds. Place the saved measurement files into the data folder and name them as self_absorption.txt and self_absorption_empty.txt. The analysis with Matlab takes these files into account, if the self-absorption correction is enabled.

5.3.2.3 Analysis of the measurement results

For analysing the measurement results, use the SScan.m Matlab-function. In the function, change the measurement file name to the correct one and choose whether the self-absorption correction for the scanner should be used. After these, no more changes are needed.

The Matlab-function parses the measurement data and modifies it for plotting the spatial responsivity distribution function (SRDF) of the sphere. The function subtracts the dark signal from the measured signal values, and multiplies the data with the self-absorption correction data. The output data is normalized to the measurement points at the bottom of the sphere. In addition, a correction is applied to the vertical angles because the scanner is positioned below the center point of the sphere, when attached to the E27-base holder. It is possible to select which one of the two holders was used for the measurement. Modifications to the Matlab function are necessary if another holder is used.

Finally, the SRDF is calculated using equation

$$SRDF(\theta,\phi) = \frac{4\pi K(\theta,\phi)}{\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} K(\theta,\phi)\sin\theta\, d\theta\, d\phi}, \tag{3}$$

where θ is the horizontal angle and ϕ is the vertical angle of the measurement. The correction factor (scf_e) used in the analysis for the external source is

$$scf_{\mathrm{e}} = 1/SRDF(\theta_{\mathrm{e}},\phi_{\mathrm{e}}), \tag{4}$$

where θ_{e} = 90° and ϕ_{e} = 315° correspond to the coordinates of the reference spot. An example of the SRDF measured for the integrating sphere is shown in Figure 5.

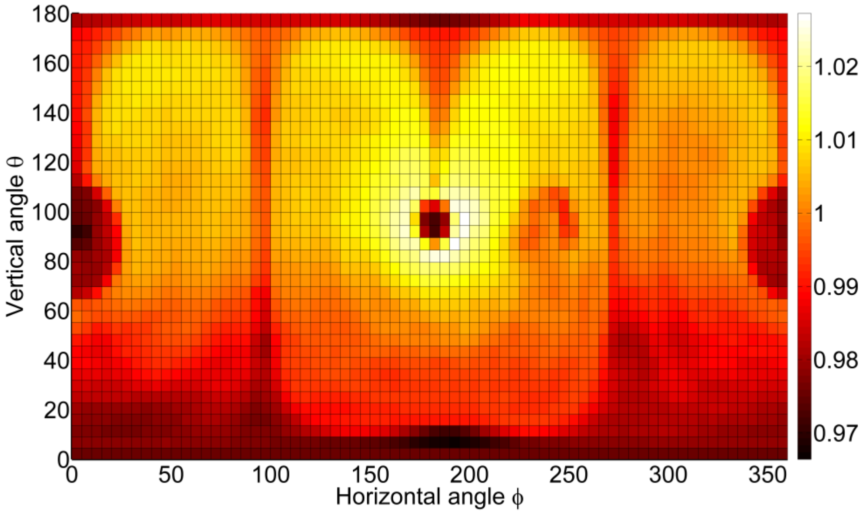

Figure 5. Scanned SRDF of the 1.65-m integrating sphere.

5.3.3. Measurement of the incident angle factor

The incident angle correction factor is measured using a narrow-beam green or white LED mounted in a lens-tube. The measurement is carried out by recording the signal of the LM-1 photometer when the LED is placed at the center of the sphere and at the optical axis of the reference luminous flux measurement, pointing towards the spot of the reference flux on the sphere surface. The distance between the light source and the center of the hot spot of the reference light should be the same in both measurements. The alignment and the positioning of the LED can be aided by using two laser beams directed inside the sphere through the reference port, one marking the center of the LED spot, and the other marking the edge of the LED spot, thus fixing the location and size of the spot.

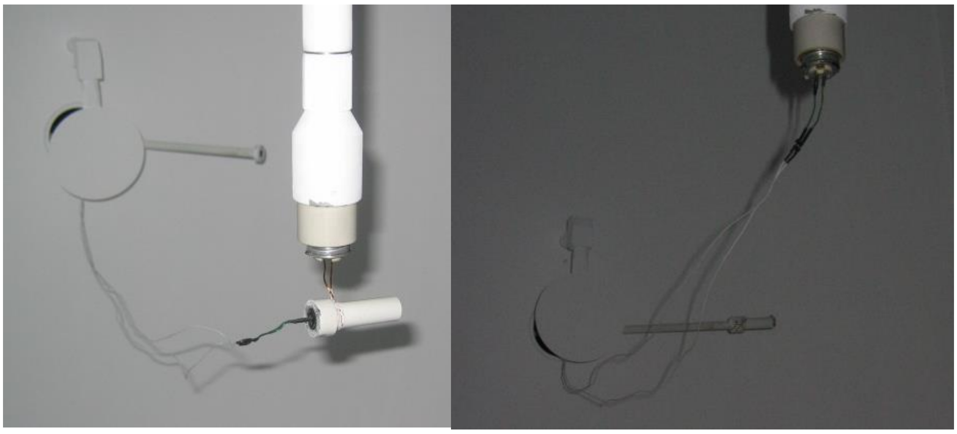

Figure 6. Configuration for measuring the incident angle correction factor.

In the measurements, the reference source is switched off, and only the LED is operated. The LED should be operated by feeding constant current, using e.g. Keithley Sourcemeter 2420, and monitoring the LED voltage. Measurement data should be recorded when the voltage reaches the value of previous measurement, i.e., at the same operating point. The deviation of the self-absorption between the two measurement sets should be taken into account by measuring the signal of an auxiliary lamp when the LED is mounted at the center of the sphere and in the axis of the reference beam.

5.3.4. Spectral throughput of the integrating sphere

The spectral throughput of the sphere is determined by measuring the spectrum of a luminous flux standard lamp inside the sphere and outside of the sphere. The spectral irradiance of the lamp is first measured on an optical rail by mounting it into an auxiliary lamp holder with the E27 base i.e. cup of the lamp is up. The polarity of the lamp used needs to be the same as in the lamp holder of the sphere. A measurement distance of 0.5-1.0 m from the lamp is suitable. A baffle with an opening of 10 cm should be used between the lamp and the diffuser head of the spectroradiometer for straylight rejection. The spectral irradiance of the lamp is measured from 3 different directions of the lamp using a spectroradiometer with 5-nm bandwidth, and an average of the measurements can be used as the spectral irradiance of the lamp $E_{ext}(\lambda)$ in the analysis. The direction can be changed by switching off the lamp, letting it cool down, and rotating the E27-base. After the irradiance measurement, the lamp is mounted in the integrating sphere, and the spectroradiometer is used for measuring the integrated spectrum $\Phi_{int}(\lambda)$ of the lamp. The relative spectral throughput of the sphere $T(\lambda)$ can then be calculated as

$$T(\lambda) = \frac{\Phi_{int}(\lambda)}{E_{ext}(\lambda)} . \tag{5}$$

In the analysis of spectral mismatch correction factors, the relative spectral throughput of the sphere is combined with the relative spectral responsivity of the photometer head LM-1 or LM-2, used in the detector port of the sphere. The method is practical for analysis of spectral-mismatch corrections of photometric measurements. For colorimetric measurements with the sphere, a calibrated spectral radiant flux standard lamp should be used. More information of the characterization measurements and analyzing of the correction factors can be found in [4]. An example of the measured relative spectral throughput is presented in Figure 7.

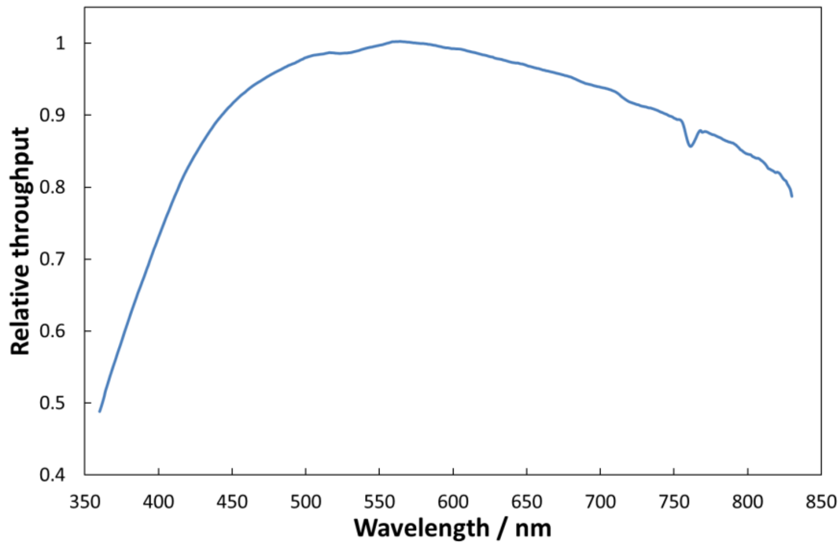

Figure 7. Relative spectral throughput of the 1.65-m integrating sphere.

6. Handling of calibration items

6.1. Safety and handling precautions

- The lamps should be turned on and off slowly (30–60 seconds). The lamps should not be moved while operated.
- Do not touch the envelope of the external source. If there are finger prints do not try to clean them. Before operating, the dust should be removed with soft brush or by blowing clean air. After operating, allow the lamp cool down for 2 hours before removing it from the setup.
- Do not touch the bulb of the internal source with bare hands. Use cotton gloves when mounting the lamps into the socket.
- Be careful when changing the internal source between calibrations. The bulb is probably still warm.
- Be very careful when handling customer lamps. Pay attention to customer wishes concerning lamp operation and handling.

6.2. Monitoring of luminous flux standard lamps

Table 5. Calibration history of the luminous flux standard lamps.

LAMP	lms9901	lms9902	lms0003	lms0004	lms0005
Current [A]	5.5380	5.6694	5.8506	5.8229	5.7338
Voltage [V]	28.812	28.849	30.133	29.603	29.326
Color temperature [K]	2721	2729	2724	2727	2716

Date	Luminous flux [lm]				
October 2003	2067.5	2158.5	2382.0	2317.0	2222.1
May 2005	2067.6	2162.8	2384.1	2316.7	2219.6
September 2006	2012.0	2167.8	2387.0	2322.6	2220.5
September 2008	2055.4	2162.8	2374.2	2307.2	2206.8
October 2009	2054.0	2170.7	2374.9	2304.4	2200.4
March 2012	2055.6	2172.0	2373.1	2304.4	2196.4
October 2014	2056.3	2171.6	2370.7	2302.7	2190.7
May 2016	2056.7	2169.6	2367.4	2296.8	2184.6

7. Uncertainty budgets

The uncertainty budget of luminous flux calibrations is presented in Table 6. More detailed information about the uncertainty budget can be found in [5].

Table 6. Uncertainty budget of luminous flux calibrations.

Source of uncertainty	**Relative standard uncertainty [%]**
System characterization and calibration	
Spatial correction factor scf_e	0.05
Spatial correction factor scf_i	0.03
Ratio of colour correction factors ccf_e / ccf_i	0.02
Correction for incident angle dependence β	0.05
Correction for illuminance non-uniformity k_a	0.03
Unit of illuminance	0.15
Transfer to standard photometer	0.10
Drift of the standard photometer	0.04
Photometer distance	0.10
Aperture area	0.01
Stray light	0.01
Drift of the reference lamp	0.01
Noise (illuminance)	0.03
Noise (reference flux)	0.02
Current measurement (illuminance)	0.01
Current measurement (reference flux)	0.05
Luminous flux measurement	

Non-linearity of the sphere photometer	0.01
Temperature increase	0.01
Noise	0.01
Current measurement	0.01
Other	
Sphere opening / closing	0.01
Repeatibility (typical)	0.05
Lamp holder	0.10
Combined standard uncertainty	0.26
Expanded uncertainty (k = 2)	0.52

8. Measurement of luminous efficacy

In addition to E27-base DC-operated standard lamps, it is possible to use the measurement facility for measurements of energy-saving lighting products, such as compact fluorescent lamps (CFLs) and light-emitting diode (LED) lamps. If E27-base 230 V lamps are to be measured, the DC-lamp holder needs to be replaced by another E27-base holder that has wiring suitable for the higher AC-voltage. For determining the luminous efficacy (lm/W) of a light source, its luminous flux and active power consumption need to be measured. In the measurements, the equipment used for photometric and spectral measurements remains the same as in the measurement of DC-operated lamps, but the equipment used for power sourcing and measurement is different. Due to the complicated spectral and angular properties of most SSLs, special care should be taken in the analysis of their spectral and spatial corrections. Correction methods for these have been described in detail in [11-13].

The AC-voltage of the lamps can be supplied using a regulating AC-voltage source of type Chroma 61601 (500 VA) or Pacific 115ASXT (1500 VA). The voltage and frequency of both devices can be programmed from the front panel of the device. In a typical luminous efficacy measurement, the measurement system is controlled using a Labview program Luminous_Efficacy_Monitoring.vi. The program initializes all meters, measures the dark current of the photometer, ignites the lamp and monitors the stabilization of the luminous flux, as well as values related to the electrical power measurement, such as active power (W), power factor and total harmonic distortion (THD).

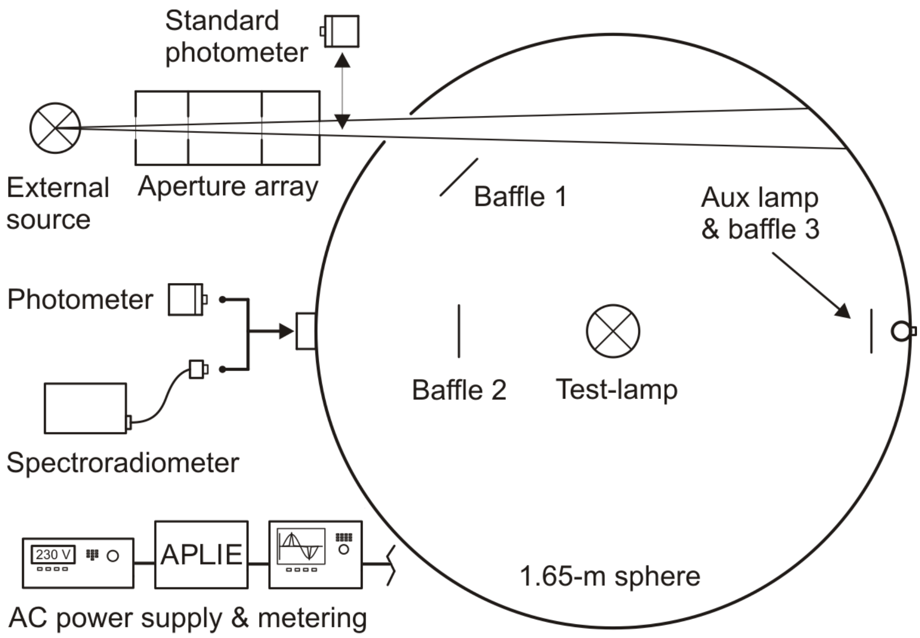

Figure 8. Integrating sphere facility configured for luminous efficacy measurement of energy-saving lighting products.

For the electrical power measurement, a Yokogawa WT-1800 power analyzer is used. The device is configured with 4 measurement channels. Channels 1-3 have 5 A current inputs with a shunt resistor size of 0.1 Ω. Channel 4 is reserved for measurements of higher currents, up to 50 A, and has a shunt resistor size of 5 mΩ. For measurements of typical low-power energy-saving lighting products, it is recommended to use channel 1 with the 5 A current input.

Due to problematic built-in power converters of energy-saving lighting products [14-16], a power line impedance emulator (APLIE) can be used between the AC-voltage source and the lamp under measurement. The passive LCR-network emulates the impedance curves of low-voltage distribution systems, and decreases the sensitivity of lamp electronics to the output impedance of the AC-voltage source. In the measurements, the APLIE is connected between the AC-voltage source and the power analyzer. In order to ensure low uncertainty of current measurements, the power analyzer voltage measurement terminals need to be connected parallel to the output of the APLIE (generator side), and the current input in series with the load (load side), see Figure 9. In the figure, the AC-source means the output terminals of the APLIE.

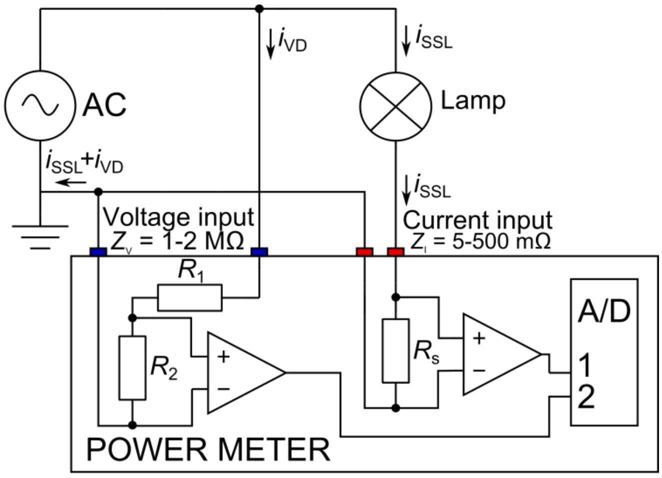

Figure 9. Wiring of the power analyzer for measurements of small currents.

9. Accommodation and environmental conditions

The photometry laboratory is the room 1559 located in the first floor of Maarintie 8 building. This laboratory is one of the clean rooms, where the dust level is kept as low as possible. The ambient temperature and the relative humidity of air still need to be recorded during the calibrations. The Clean Zone-aggregate should be on to filter the dust from air.

10. Control data

The usage of the luminous flux standard lamps is monitored by using a logbook. The logbook is kept in the same closet with the lamps. Each lamp has its own sheet with the following columns: date, user, burn start time, burn stop time, total burning time so far and base voltage.

The measurement data, both raw and analyzed, are stored in the author's computer. The names of the data files are written on the measurement notes. The data is organized by creating a folder for each customer.

11. Certificates

Calibration certificates are handled according to [8]. The following information needs to be included in the certificate:

- Ambient temperature and relative humidity.
- Luminous flux of the standard lamp with corresponding operating current and base voltage.

- Burning time of the lamp during the calibration and total burning time after the calibration if the information is available.

12. Intercomparisons

The latest international comparisons of the unit of luminous flux:

- 2000: Comparison of luminous flux units with NIST (USA) [9]

Level of agreement 0.06 % with an expanded uncertainty (k = 2) of 1.01 %.

- 2003: Comparison of luminous flux units with SP (BIPM calibration in 2001)

Level of agreement 0.16 % with an expanded uncertainty (k = 2) of 1.10 %.

- 2008: Luminous Flux EURAMET.PR.-K4 Key-Comparison

Level of agreement 0.03 % with an expanded uncertainty (k = 2) of 0.76 %.

13. Publications

[1] Quality Manual of Luminous Intensity Laboratory

[2] Quality Manual of Spectral Irradiance Measurements

[3] Ohno Y., “Detector-based luminous-flux calibration using the Absolute Ingrating-Sphere Method”, *Metrologia*, **35**, 473-478 (1998)

[4] Hovila J., “Characterisation of the national measurement standard of luminous flux”, Master’s Thesis (2001) (*In Finnish*)

[5] 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).

[6] MRI calibration schedule: http://metrology.hut.fi/quality/Calsched.pdf

[7] Instruction Manual for Operating Standard Lamps

[8] http://metrology.hut.fi/quality/AnnexD.pdf (instructions for writing calibration certificates)

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

[10] T. Pulli, ”Energiansäästölamppujen valotehokkuuden mittaaminen, ” B.Sc. thesis, Aalto University, 34 p. (2010). In Finnish

[11] T. Pulli, “Goniospektrometri ledien karakterisointiin”, Optisen teknologian erikoistyö, Aalto-University, 37 p. (2011). In Finnish

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[13] A. Vaskuri, “Energiansäästölamppujen sähköiset karakterisoinnit,” B.Sc. thesis, Aalto University, 44 p. (2011). In Finnish

[14] T. Koskinen, “Sähköverkon impedanssin vaikutus energiansäästölamppujen valotehokkuuden mittauksissa,“ M.Sc. thesis, Aalto University, 63 p. (2013).

[15] T. Poikonen, T. Koskinen, H. Baumgartner, P. Kärhä, and E. Ikonen, ”Adjustable power line impedance emulator for characterization of energy-saving lamps,” In Proc. NEWRAD 2014, Espoo, Finland (2014).

[16] T. Poikonen, “Characterization of Light Emitting Diodes and Photometer Quality Factors,” Doctoral thesis, Aalto University, Espoo, Finland, 92 p. (2012).