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Instruction Manual of Luminance and Spectral Radiance Calibrations

Version 2.8

13/12/2018

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 luminance ($cd \cdot m^{-2}$) and spectral radiance ($W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}$) calibrations. The calibrated devices can be either sources or meters.

2.2. Object and field of application

Reference photometer: Primary standard for luminance and spectral radiance calibrations. Used for calibrating the secondary standard luminance meter.

Luminance meter: Secondary standard for luminance and spectral radiance calibrations. Used for customer calibrations.

Spectroradiometer: Used for measuring the spectrum of the spectral radiance source.

Integrating sphere: Uniform light source used in luminance / spectral radiance meter calibrations.

2.3. Features

a) Reference photometer

See Ref. [1].

b) Luminance meter

A commercially available luminance meter LMT L-1009 (manufacturer LMT Lichtmesstechnik GmbH, Berlin) is used in customer calibrations. The luminance meter is calibrated against the reference photometer using an integrating sphere with known output aperture as a light source.

c) Spectroradiometer

See Ref. [2].

d) Integrating sphere

A commercially available integrating sphere light source (manufacturer Labsphere Inc.) is used as a uniform light source in calibrations. The luminance / spectral radiance level is adjusted with integrated iris diaphragms and different sets of lamps illuminating the sphere.

[1] Quality Manual of Luminous Intensity Laboratory

[2] Quality Manual of Spectral Irradiance Measurements

3. Principle of the realization

The principles of the realization of luminance and spectral radiance have been described thoroughly in Ref. [3]. Therefore only a brief description is given here.

3.1. Luminance

The luminance of a light source (integrating sphere with known output aperture) is determined from the measurement geometry and the illuminance measured with a photometer [1]. The luminance of the light source is obtained as

$$L_v = \frac{E_v \cdot D^2}{A}, \qquad (1)$$

where E_v is the illuminance at the effective distance D between the aperture planes of the source and the photometer, and A is the area of the source aperture. The effective distance depends on the radius of the photometer aperture r_1, the radius of the source r_2, and the physical distance d between the two apertures according to the relation

$$D^2 = r_1^2 + r_2^2 + d^2. \qquad (2)$$

Equation (2) is accurate within ± 0.01 % for distances which are more than one order of magnitude greater than the radii of the two apertures [4].

3.2. Spectral radiance

Spectral radiance $L_e(\lambda)$ and luminance are linked by

$$L_v = K_m \int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} L_e(\lambda)\, V(\lambda)\, \mathrm{d}\lambda, \qquad (3)$$

where K_m = 683 lm·W^{-1} is the maximum spectral luminous efficacy of radiation for photopic vision and $V(\lambda)$ is the spectral sensitivity of a human eye [5].

Spectral radiance is determined by measuring the luminance $L_{v,m}$ and the relative spectral irradiance of the output of the integrating sphere source. A luminance value $L_{v,c}$ is calculated from Eq. 3 with the measured spectrum, and a normalization factor

$$k = \frac{L_{v,m}}{L_{v,c}} \qquad (4)$$

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

[4] Kostkowski H. J., "Reliable spectroradiometry", Spectroradiometry Consulting, (1997)

[5] CIE Publication 18.2, "The basis of physical photometry", (1983)

is determined. The spectral radiance is then obtained by multiplying each spectral component by the normalization factor.

4. Equipment

4.1. Luminance

Equipment needed in luminance meter calibrations is presented in Table 1 and Table 2.

Table 1. Equipment needed in the calibration of the secondary standard luminance meter.

Description	Quantity	Serial NR/Identification
A. Reference photometer		
See Ref. [1].	1	UVFR-5/UVFR-8, NFRA1/HUT-7, cdf9502/cdf9401
B. Spectroradiometer		
See Ref. [2]	1	Konica Minolta CS-2000A
C. Luminance meter		
1. Luminance meter	1	LMT L-1009
D. Optical bench		
1. Optical rail system (1.5 m)	1	R-2, Movetec Oy
2. Calibrated length scale	1	To be calibrated
3. Carriage for the photometer	1	Part of rail system, Movetech Oy
4. Calibrated length block	1	Precalibrated or calibrated on-site using the rail system
5. Baffle frame	1	
6. Electronic shutter with adjustable aperture	1	Melles Griot 04-IES-215 ∅ 5–63 mm / 04-IES-213, ∅ 2–35 mm
7. Baffle adapter for shutter	1	BAS-1 / BAS-2
8. Mechanical elevator	1	
E. Light source		
1. Halogen lamp	4	50W,12V, MR16
2. Integrating sphere	1	Labsphere US-120-SF
3. Satellite sphere	2	Labsphere (∅ 10cm)
4. Output precision aperture	4	AL1, AL2, AL3, AL4
5. Lamp power supply	1	Heinzinger PTN55 125-10
6. Standard resistor (100mΩ)	1	Guildline 9230-15: 62587/SR96, 65852 / SR-00
7. Digital voltmeter	1	HP3458A, HP34401A, Agilent 34410A, Keysight 34461A
F. Alignment system		

1. Alignment laser	1	OMTec
2. Auxiliary mirror	1	
G. Control and data acquisition		
1. Computer	1	PC with access to MIKES-Aalto file system.
2. Current-to-voltage converter	1	Lab Kinetics SP042, MRI CVC
3. Digital voltmeter	2	HP 3458A
4. GPIB-USB adapter	1	NI GPIB-USB-HS
5. Software	2	Luminance_TKK.vi

Table 2. Equipment needed in customer's luminance meter calibration.

Description	Quantity	Identification
A. Luminance meter		
As in table 1	1	LMT L-1009
B. Spectroradiometer		
As in table 1	1	Konica Minolta CS-2000A
C. Optical table		
1. Magnetic base plate	1	
2. Post holder	2	
D. Light source		
1.-7. as in table 1	5	1, 2, 2.5, 3, 3.5 in.
8. Output limiting aperture		
E. Alignment system		
1. Alignment laser if needed	1	OMTec
F. Control and data acquisitions		
1. as in table 1		
2. Software	1	Luminance_customer.vi

4.2. Spectral radiance

Equipment needed in customer's spectral radiance calibrations is presented in Table 3.

Table 3. Equipment needed in customer's spectral radiance calibration.

Description	Quantity	Identification
A. Luminance meter		
As in table 1	1	LMT L-1009
B. Spectroradiometer		
As in table 1	1	Konica Minolta CS-2000A
C. Optical table		
As in table 2		
D. Alignment system		

As in table 2	
E. Control and data acquisition	
Digital voltmeter	HP 3458A / HP 34401A

4.3. Maintenance

To ensure accurate measurement results and traceability, the devices used in the calibrations must be calibrated often enough. Calibration schedule of the photometric equipment is presented in Table 4. Other equipment is calibrated according to the calibration schedule of the Metrology Research Institute. Correlated colour temperature of the integrating sphere light source is adjusted using a Konica Minolta CS-2000A spectroradiometer during all luminance and spectral radiance calibrations.

Table 4. Calibration schedule of the photometric equipment.

Device to be calibrated	Calibration interval [years]
Reference photometer	1
Luminance meter	2
Spectroradiometer	See Ref. [2].
Precision apertures	4

5. Measurement traceability

5.1. Traceability chain of luminance

The unit of luminance is linked to the unit of luminous intensity via the photometer. Therefore luminance is traceable to the national primary standards of optical power, spectral transmittance and length. The traceability chain of the unit of luminance is presented in Figure 1.

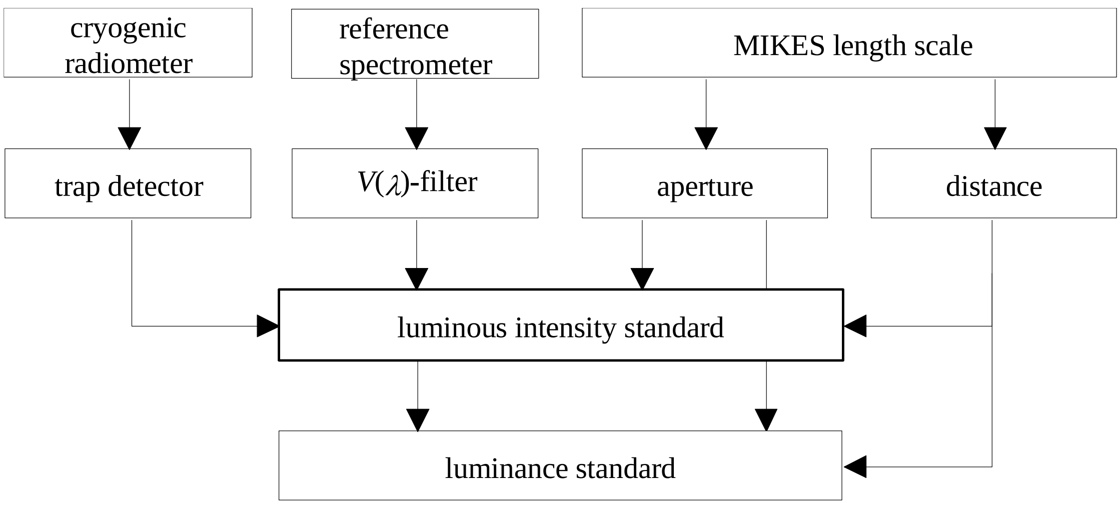

Figure 1. Traceability chain of the realization of the unit of luminance.

5.2. Traceability chain of spectral radiance

The unit of spectral radiance is linked to the units of luminance (Figure 1) and spectral irradiance via luminance meter and a spectroradiometer. Spectral irradiance is traceable to the national standards of voltage, current and resistance [2].

5.3. Uncertainty budget

An uncertainty budget for the units of luminance and spectral radiance (for simplicity only at a wavelength of 600 nm) is presented in Table 5. The wavelength-dependent combined standard uncertainty of the spectral radiance is presented in Figure 2.

Table 5. Uncertainty budget of luminance and spectral radiance calibrations.

Source of uncertainty	100 x relative standard uncertainty	
	L_y	L_e (600 nm)
Illuminance / spectral radiance standard	0.15	0.25
Integrating sphere source		
Aperture area (diameter 16 mm)	0.02	0.02
Spatial non-uniformity	0.09	0.07
Instability	0.04	0.04
Colour temperature	0.01	0.01
Spectroradiometer		
Wavelength scale		0.04
Spectral distortion		< 0.01
Spectral scattering		< 0.01
Drift of the photomultiplier tube		0.03
Noise of the photomultiplier tube		0.08
Calibration of the spectroradiometer		0.11
Temperature dependence of irradiance		0.05
Non-linearity of photometer	0.01	0.01
Photocurrent measurement	0.01*)	0.01
Alignment	< 0.01	< 0.01
Distance measurement (800 mm)	0.03	0.03
Diffraction	< 0.01	< 0.01
Combined standard uncertainty	0.18	0.31
Expanded uncertainty (k = 2)	0.36	0.62

*) At low luminance or radiance levels, increased uncertainty in photocurrent measurement needs to be accounted for.

More detailed information about the uncertainty budget is found in Ref [3]. Since comparison evidence of luminance and spectral radiance calibrations does not exist, the official uncertainty levels are higher:

Bureau International des Poids et Mesures (BIPM) approved calibration and measurement capability (CMC [6]) expanded uncertainties (k = 2) for luminance are 0.8 % (range 1-10000 cd m^{-2}) and 1.0 % (range 10000-40000 cd m^{-2}) and for spectral radiance 3.3-1.4 % (range 360-430 nm), 1.4 % (range 430-700 nm) and 1.4-4.2 % (range 700-830 nm).

When calibrating the L-1009 luminance meter at small measurement angles, the increased inhomogeneity of the integrating sphere source and the noise in the signal of the luminance meter at small measurement angles must be taken into account, particularly at low luminance levels.

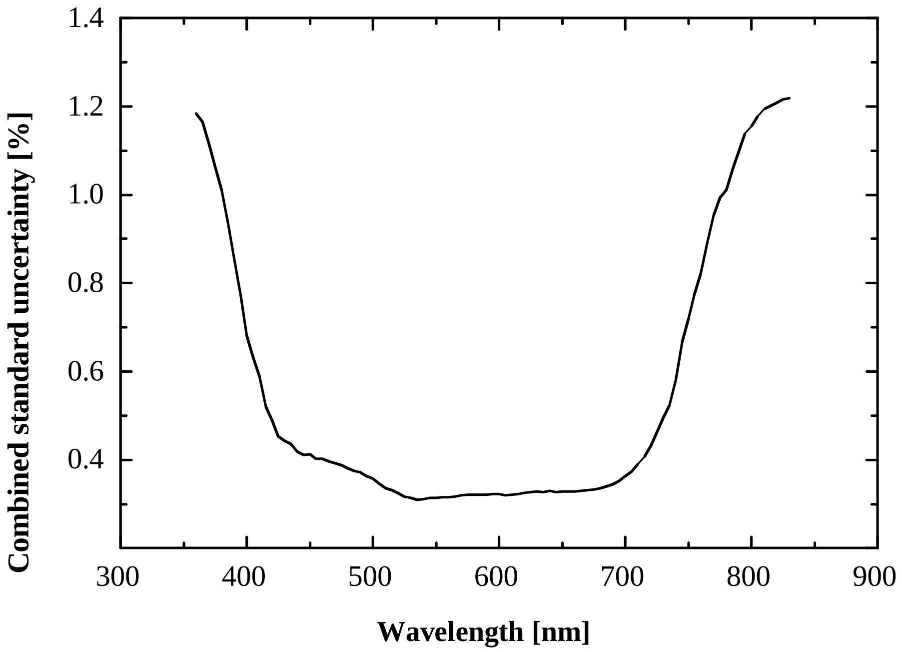

Figure 2. Combined standard uncertainty of the unit of spectral radiance as a function of wavelength.

6. Calibration methods and procedures

A typical luminance and spectral radiance measurement setup is presented schematically in Figure 3 and as a photograph in Figure 4. The reference photometer, luminance meter and the spectroradiometer are placed on an optical table. The spectroradiometer can be installed behind the luminance meter, at a distance of 1.0-1.2 m from the sphere source.

[6] kcdb.bipm.fr/BIPM-KCDB/AppendixC/

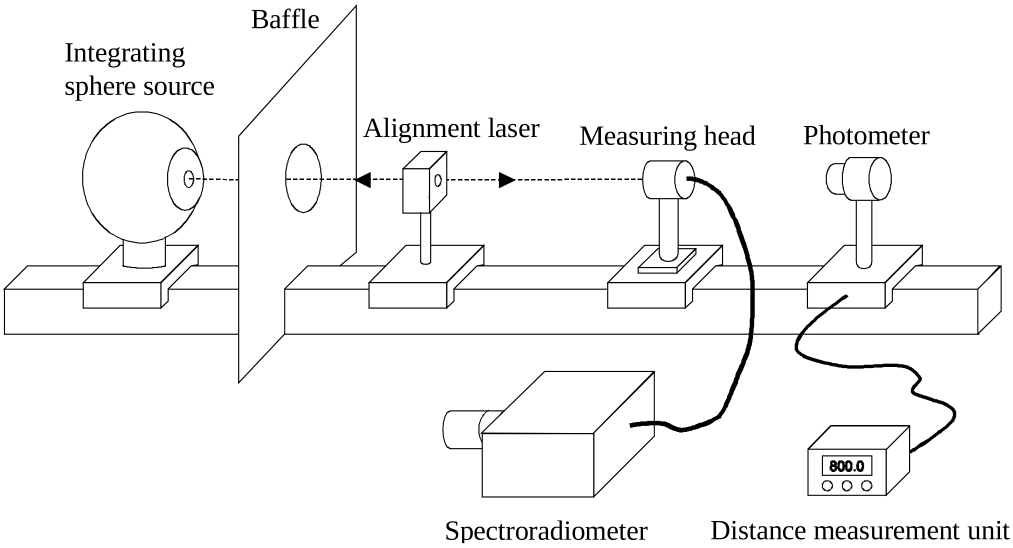

Figure 3. A typical luminance and spectral radiance measurement setup.

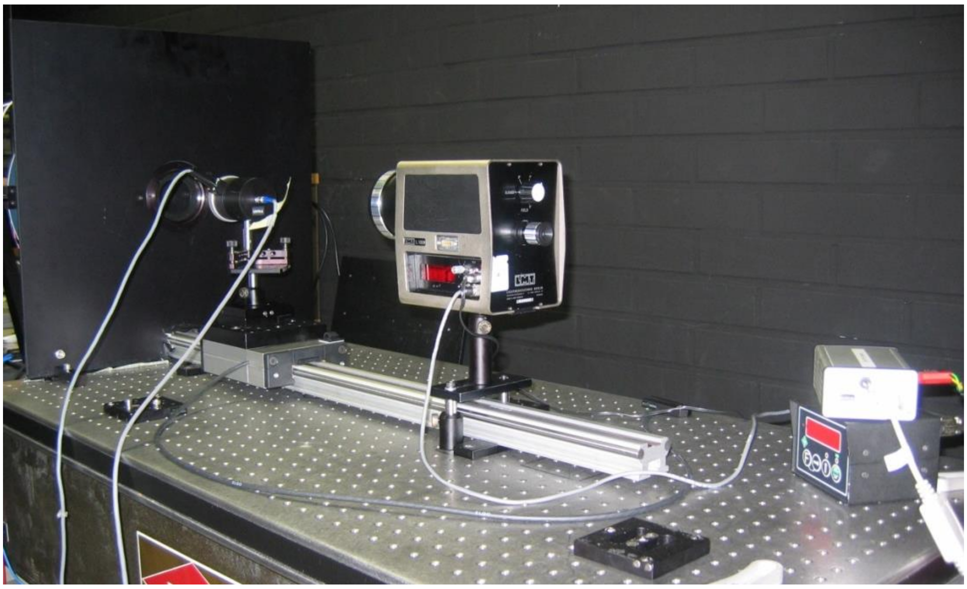

Figure 4. Photograph of the luminance measurement setup. (to be updated for the new rail)

The current of the lamps illuminating the integrating sphere source is monitored by using a single value precision resistor and a digital voltmeter (DVM). The voltage of the lamps can be checked with an additional pair of wires connected parallel to the current terminals of the integrating sphere source. The photocurrent of the photometer is measured using a current-to-voltage converter (CVC) and another DVM. Analog output of the L-1009 luminance meter is connected to this DVM also.

6.1. L-1009 luminance meter calibration

The L-1009 luminance meter is calibrated every two years. The measurement program **Luminance_TKK_2017.vi** is used in the calibration of all scales. The program can be found in the measurement computer (see Table 1) in directory:

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

6.1.1. Integrating sphere alignment and aperture selection

The sphere is supported by rigid, black-anodized aluminum structure. The supporting structure is attached to the optical table with M6 screws. Two of these screws also hold the black-anodized baffle frame, approximately 10 cm from the sphere opening.

The vertical tilt of the sphere is cancelled by using an adjustment screw under the sphere. The fixed location of the integrating sphere determines the optical axis: 25 cm above the surface of the table. The optical axis is visualized by using a two-beam alignment laser positioned between the detectors and the integrating sphere source. The detectors are removed and the beam is directed along the table by aiming the beams to the centre of the sphere output and to the marking on the opposite wall. A shielding cap covering the sphere output has a small hole in the middle of it to make the alignment easier. The cancellation of the sphere tilt can be verified by placing a mirror in front of the aperture. The back reflection from the mirror should hit the output of the laser.

There are four precision apertures that can be used in HUT luminance meter calibration; two with a diameter of 8 mm (AL1, AL3) and two with a diameter of 16 mm (AL2, AL4). Detailed aperture characteristics are presented in Table 6. All apertures are mounted on the sphere with the sharp edge facing the detectors. Usually the aperture AL2 is used in luminance meter calibration.

Table 6. Aperture areas and uncertainties.

Aperture	Aperture area [mm^2]	Uncertainty (k = 2)	Calibrated by MIKES
AL1	50.728	0.10 %	2002
AL2	201.595	0.06 %	2016
AL3	50.708	0.15 %	1999
AL4	201.372	0.08 %	1999

6.1.2. Alignment and measurement distance of the detectors

The 1.5-m magnetic measurement rail is located on the photometry laboratory. The rail has a rail carrier on which the photometer is mounted using a magnetic base plate. Opto-mechanical components needed for alignment procedure are shown in Table 7.

Table 7. Mechanical components needed for alignment of the devices. (Obsolete. To be updated for the new rail)

Detector	Components from down to up
Photometer	Magnetic base plate, 25-mm post holder, 40-mm post, tilt stage, 30-mm post, and photometer itself.
Luminance meter	Specific fixed assembly including magnetic base plate (see Figure 4), 75-mm post holder, 50-mm post, and LMT L-1009.
Spectroradiometer	Mechanical elevator.
Alignment laser	Aluminum holder to the rail, 100-mm post holder, 100-mm post, small tilt stage, and laser itself.

The photometer is mounted at approximate distances of 20 cm and 80 cm from the sphere. The photometer is aligned using the back-reflection of the $V(\lambda)$ filter when the photometer is mounted on the base plate 80 cm from the sphere. The photometer is aligned so that the laser beam goes through the centre of the aperture of the photometer and reflects from the filter back to the output of the laser.

The distance x between the front surfaces of the sphere and the photometer is measured mechanically. Overall distance S between the aperture planes is

$$S = x + 3.0 + 3.2 \text{ mm}, \tag{5}$$

where 3.0 mm is the distance between the photometer front surface and the photometer aperture and 3.2 mm is the distance between the sphere front surface and the sphere aperture.

The photometer is temporarily removed and the luminance meter is mounted without magnetic base plate on the table behind the photometer. In terms of alignment and focusing, the luminance meter works like a camera; the object to be measured can be seen by looking into the eyepiece of the meter. The meter is focused on the aperture plane of the integrating sphere. The measurement area is indicated by a black circle, whose size can be changed by adjusting the measurement solid angle. The distance setting of the luminance meter is selected so that the measurement area with the 1° measurement angle is at least 20 % smaller than the sphere aperture. This needs to be taken into account in all measurements, as the effective measurement angle is always slightly larger than the measurement spot seen through the objective lens.

6.1.3. Spectroradiometer

The CS-2000A spectroradiometer is operated in the radiance measurement mode, and its objective lens is focused on the aperture plane of the integrating sphere source in a similar way as the luminance meter. The CS-2000A is used for checking the correlated colour temperature of the source, when adjusting its luminance level. At each luminance level, the currents of the lamps and the settings of the iris diaphragms need to be adjusted as long as the CCT of the source is 2856 ± 2 K. With luminance levels below 10000 cd/m^2, the 1 deg measurement angle can be used. Above 10000 cd/m^2, a smaller measurement angle should be used to avoid saturation of the CS-2000A meter.

6.1.4. Baffle and shutter

An electronic shutter with an adjustable iris (usually set in diameter 40 mm) is placed between the integrating sphere and the detectors. The shutter is attached to a baffle with special screw disk and a baffle is attached to the baffle frame with two M4 screws. The electronic shutter is controlled via the serial bus.

6.1.5. Lamps

The sphere has four separate light sources utilizing MR16 halogen lamps with aluminium reflectors [7]. Two of the light sources (marked as 1 and 2) are on opposite sides of the sphere and equipped with opal glass discs to provide better luminance uniformity on the sphere output. The luminance level is adjusted by using iris diaphragms within these light sources. The other two light sources (marked as 3 and 4) are operated separately and do not have opal glasses nor iris diaphragms. Four switches under the sphere are used for lamp selection. The lowest luminance levels below 150 cd/m^2 are produced using one of the halogen lamps together with a small integrating sphere for attenuating the light level. This so called “satellite sphere” is equipped with two adjustable iris diaphragms for fine-tuning of the luminance level. (Figure 1). With careful adjustment of the currents and irises, it is possible to maintain the CCT of 2856 K even with the smallest luminance levels.

[7] Philips Brilliantline Pro Alu 50W GU5.3 12V 36D

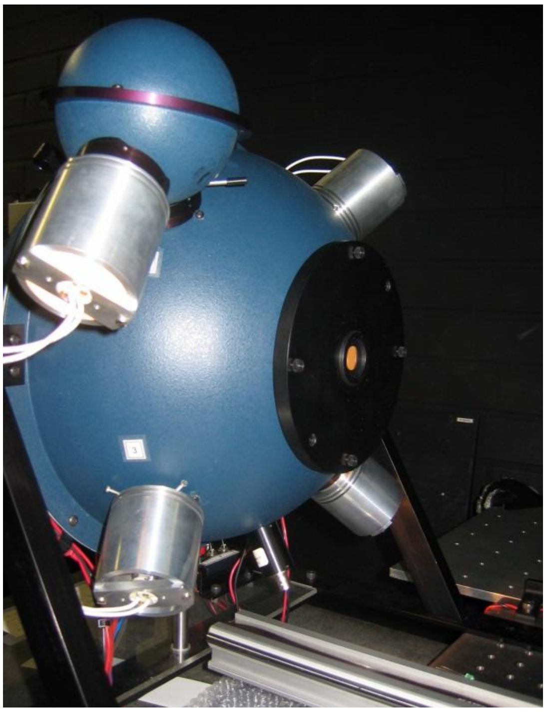

Figure 5. Satellite sphere mounted to port 1 for reaching the lowest luminance levels.

The luminance source characteristics with different amounts of light sources operated are presented in Table 8. The correlated colour temperature of the source is affected by the amount of lamps, size of the output aperture, and the openings of the irises.

Table 8. Characteristics of the integrating sphere source. The actual luminance ranges and driving currents depend on the type and condition of the light sources used.

Number of light sources	1	2	3	4
Current [A]	4.09	4.14	3.86	3.82
Voltage [V]	11.97	22.38	30.31	39.90
Color temperature [K]		2770 – 2835	2840 – 2870	2845 – 2865
Luminance range[8] [$cd \cdot m^{-2}$]	1 – 1000	140 – 12000	17000 - 26000	33000 - 41000

The lamps are connected in series, which means that the current is the same for each lamp and the voltage is measured across all lamps.

CAUTION! When the number of light sources needs to be changed, the lamp current must be turned down before switches are turned on or off. After that the current is adjusted according to Table 8.

[8] Luminance range when using aperture AL2. Luminance depends on the size of the output aperture.

6.1.6. Measurement

The L-1009 luminance meter is calibrated across the whole luminance range of the integrating sphere by 18 calibration points, presented in Table 9. The correction for the reading of the L-1009 luminance meter is determined at three luminance levels for its each scale of the display unit. Since the repeatability of the iris diaphragm adjustment is poor, the luminance values below are advisory.

Table 9. The approximate calibration points of the L-1009 luminance meter.

<table>
<tr><th>Number of light sources</th><th>Iris diaphragms open</th><th>Calibration luminance [cd m⁻²]</th><th>Scale of display of luminance meter</th></tr>
<tr><td rowspan="2">4</td><td>100 %</td><td>40500</td><td>200k</td></tr>
<tr><td>0 %</td><td>33000</td><td>200k</td></tr>
<tr><td rowspan="2">3</td><td>50 %</td><td>22000</td><td>200k</td></tr>
<tr><td>10 %</td><td>18000</td><td>20k</td></tr>
<tr><td rowspan="5">2</td><td>90 %</td><td>10000</td><td>20k</td></tr>
<tr><td>30 %</td><td>2200</td><td>20k</td></tr>
<tr><td>20 %</td><td>1800</td><td rowspan="3">2k</td></tr>
<tr><td>10 %</td><td>1000</td></tr>
<tr><td>5 %</td><td>250</td></tr>
<tr><td rowspan="9">1</td><td>100 %</td><td>180</td><td rowspan="3">200</td></tr>
<tr><td>50 %</td><td>100</td></tr>
<tr><td>30 %</td><td>40</td></tr>
<tr><td>10 %</td><td>18</td><td rowspan="3">20</td></tr>
<tr><td>5 %</td><td>10</td></tr>
<tr><td>4 %</td><td>4.0</td></tr>
<tr><td>3 %</td><td>1.8</td><td rowspan="3">2</td></tr>
<tr><td>2 %</td><td>1.5</td></tr>
<tr><td>1 %</td><td>1.0</td></tr>
</table>

With both iris diaphragms open, all four lamps are operated and allowed to stabilize for at least 30 minutes. After the stabilization, the luminance is calibrated at the maximum luminance level*). The illuminance is measured with the photometer attached to the magnetic base plate on the rail carrier 80 cm from the sphere aperture. The first (absolute) illuminance measurement includes 30 measurement samples (10 × dark current + 20 × illuminance current). The electronic shutter, which is controlled via the serial bus by the LabVIEW program, is utilized for measuring the dark current.

Next, a relative illuminance value corresponding to the maximum luminance is measured by moving the photometer to the magnetic base plate close to the sphere. Dark current measurements are no more necessary. After illuminance measurement, the photometer is temporarily removed and the luminance is measured with the luminance meter at measurement angles of 1°, 20’ and 6’. Alternatively, the measurements can be carried out using a fixed measurement angle of 1°. The luminance meter has a display for measured luminance. However, higher accuracy is achieved by using an analog output which gives voltage values that can be converted into luminance values. The voltages are measured with the same DVM as the signal from the photometer, but from the other (rear) terminal. One should take care during the calibration that the voltages are always measured using the right terminal.

This procedure is repeated for 18 remaining luminance levels. The relative values are turned into absolute values during data analysis by using the first absolute calibration point as a reference.

*) To calibrate spectral radiance at the same time, the spectrum is measured first. See Section 6.2.

6.1.7. Data analysis

Calibration data is analysed using the same LabVIEW file as in the measurements.

6.2. Spectral radiance calibration of the integrating sphere source

The absolute spectral radiance of the integrating sphere source is needed for calibration of spectral radiance meters. Obtaining the spectral radiance of the integrating sphere source is described in Section 3.2. First, the luminance of the sphere is measured using the photometer during the luminance calibration or afterwards using the calibrated luminance meter. Then, the relative spectral irradiance is measured using a calibrated spectroradiometer. If a scanning spectroradiometer with a separate diffuser head is used, the signal-to-noise ratio can be improved by positioning the diffuser head close to the sphere opening, for example 20 cm from the sphere output. It is not recommended to measure the spectrum at the aperture plane, as the measured spectrum may be sensitive to the measurement geometry.

Within the measurement range for luminance calibrations, the spectral radiance varies between [$5\cdot10^{-4}$…$5.25\cdot10^{0}$ W m^{-2} sr^{-1} nm^{-1}]. CMC-approved spectral radiance measurement range of the Metrology Research Institute is 10^{-4} – 1 W m^{-2} sr^{-1} nm^{-1}.

6.3. Calibration of the CS-2000A radiance responsivity

The CS-2000A spectroradiometer can be used in irradiance and radiance measurement modes. The absolute spectral irradiance responsivity of the device is calibrated using a diffuser head that can be attached in front of the objective lens (see Ref. [2]). The calibration of the irradiance mode is transferred to the radiance mode using the L-1009 luminance meter and the integrating sphere source.

It is recommended to operate the integrating sphere source with the same output aperture as in the calibration of the L-1009 luminance meter, as its size is optimal for this calibration. The L-1009 luminance meter and the CS-2000A spectroradiometer should be aligned on the optical axis of the setup at a distance of approximately 0.8 m from the luminance source. Then, the 1° measurement angle can be used with both devices. Baffles should be used between the source and the CS-2000A for straylight rejection, when measuring in the irradiance mode. The luminance level of the sphere is first adjusted close to 10000 cd/m^2 and CCT of 2856 K. The sphere should let to stabilize for at least 1 hour before the measurements begin.

The luminance of the sphere output is measured using the luminance meter with the 1° measurement angle. Then, the relative spectral irradiance is measured using the calibrated CS-2000A with the diffuser head. The spectral radiance of the source is calculated from the measurement results as described in Section 3.2. Then, the diffuser of the CS-2000A is removed, and the device is focused in the centre of the sphere output using the 1° measurement angle. The calculated radiance and measured non-corrected radiance of the source are used for calculating the calibration file for the CS-2000A. More information about the CS-2000A calibration procedures can be found in Ref. [9]. The calibration file should be saved in the CS-2000A according to the naming conventions of Ref. [9]. It is then possible to load the calibration of either irradiance or radiance mode without recalibration of the device.

6.4. Customer calibrations

Customer devices are either sources or meters. The sources should be used according to the given specifications, such as operating current. Number of measurement points, typically 5 – 7, is agreed with the customer.

An optical rail with meters mounted on rail carriers can be used in customer meter calibrations. The rail can be attached to the optical table either perpendicularly or parallel to the optical axis, depending on the case.

6.4.1. Luminance

a) Luminance source

The luminance of the source is measured with the L-1009 luminance meter. The measurement angle of the luminance meter should be chosen close to the size of the output aperture of the source, but about 20 % smaller. Typically the 1° measurement angle is used. Measurement angles smaller than 1° should be avoided, because the calibration becomes sensitive to the possible inhomogeneity of the luminance source.

b) Luminance meter

The luminance of the integrating sphere is measured with the L-1009 luminance meter and compared against the customer's luminance meter. The measurement program **Luminance_customer.vi** is in the measurement computer (see Table 1) in directory:

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

The integrating sphere has a set of different-sized limiting apertures for luminance meters with different measurement angles. The luminance source characteristics with different amounts of light sources at five apertures operated are presented in Table 10.

[9] Instruction manual for Konica Minolta CS-1000 and CS-2000 spectroradiometers

The sphere aperture and distance from the device under calibration to the aperture should be set so that the measurement area in the aperture is at least 20 % smaller than the aperture itself.

Table 10. Luminance sphere characteristics. The actual luminance ranges and driving currents depend on the type and condition of the light sources used.

Number of light sources	1	2	3	4
Current [A]	4.09	4.14	3.86	3.82
Exit port configuration		Luminance range [cd·m^{-2}]		
AL2 aperture	1 – 1000	140 – 12000	17000 – 26000	33000 – 41000
10-cm opening (without any aperture)	1 – 500	60 – 5300	7500 – 11300	14700 – 18200
7.5-cm opening		75 – 6600	9800 – 14000	18500 – 22300
6.25-cm opening		85 – 7500	11000 – 15700	20700 – 25000
5-cm opening		100 – 8400	12400 – 17600	23200 – 28000

6.4.2. Spectral radiance

a) Spectral radiance source

The spectral radiance of the customer’s source is measured with the L-1009 luminance meter and the CS-2000A spectroradiometer as described in Section 6.2. The CS-2000A can be used in the radiance mode, but the luminance level measured with the L-1009 is used for determining the absolute value. If the wavelength range 380-780 nm of the CS-2000A is not sufficient, a scanning spectroradiometer should be used to cover the spectral range required. With low spectral radiance levels, long integration times need to be used. If a scanning spectroradiometer is used, spectral bandwidth of 5 nm is recommended. Averaging of a few measurements to improve the signal-to-noise ratio can be used as well.

b) Spectral radiance meter

The spectral radiance of the integrating sphere source is measured with the L-1009 luminance meter and the CS-2000A spectroradiometer and compared against the customer’s spectral radiance meter. The output aperture of the sphere should be chosen as described in Section 6.4.1.

7. Accommodation and environmental conditions

The photometry laboratory is the room 1559 located in the first floor of Maarintie 8 building.

During luminance and spectral radiance calibrations:

- The Clean Zone -aggregate should be on to filter the air from dust.
- The temperature level should be monitored.

- The humidity level should be monitored.

8. Records

The measurement data coming from the calibrations and development of equipment is archived. To write down important parameters during the L-1009 luminance meter calibration, the comment text field in the LabVIEW program is utilized.

The measurement notes (date, set-up, raw data) are automatically written to a measurement data file during the measurements. The measurement data, both raw and analyzed, are stored in author's computer. The names of the data files are written on the measurement notes. The data is organized by creating an own folder for each customer.

9. Certificates

Calibration certificates are handled according to [10]. Include in the calibration certificate:

- Ambient temperature and relative humidity
- Luminance and spectral radiance source: Source voltage and current, luminance / spectral radiance values with specified settings, e.g. shutter positions, monitor detector readings etc.
- Luminance and spectral radiance meter: Settings of the meter, reference and calibrated values with corresponding correction factors.
- Measured spectral radiance values and calculated uncertainties as an attachment on the certificate and/or computer disk.

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