Aalto University

School of Electrical Engineering

Metrology Research Institute

Aalto University
School of Electrical
Engineering

Jari Hovila

Pasi Manninen

Tuomas Poikonen

Tomi Pulli

Janne Askola

Ville Mantela

Digitally signed
by Janne Askola
Date: 2020.12.11
11:06:14 +02'00'

Aalto University

# Quality Manual of Luminous Intensity Laboratory

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Aalto University
School of Electrical
Engineering

# 1. Table of contents

# 2. Definition

## 2.1. Scope

This quality manual describes the principle and the operation of the equipment used for detector-based luminous intensity (cd) and illuminance (lx) measurements.

## 2.2. Object and field of application

*Reference photometer*: Primary standard for luminous intensity and illuminance measurements. Used for calibrating primary standard lamps and secondary standard photometers.

*PRC photometer*: Secondary standard for luminous intensity and illuminance measurements. Used for calibrating customer standard lamps and photometers.

*LMT photometer*: Secondary standard for luminous intensity measurements of light-emitting diodes (LEDs). Compliant with the requirements of CIE standard 127 [1].

## 2.3. Features

a) Reference photometer

The reference photometer consists of a trap detector, a $V(\lambda)$ filter, a copper oven for temperature stabilization of the filter, and a precision aperture. The components form a compact and robust photometer. The expanded uncertainties ($k$ = 2) of luminous intensity and illuminance measurements are 0.36 % and 0.31 %, respectively.

b) PRC photometers

A commercially available PRC photometer HUT-2 (manufacturer: PRC Krochmann GmbH) is used for customer calibrations. Photometer HUT-1 is normally used only for maintaining the illuminance responsivity scale. LM-1 and LM-2 are used as sphere photometers in luminous flux measurements. The photometers are calibrated with direct comparison against the reference photometer using a stable standard lamp as a light source. The expanded uncertainties ($k$ = 2) of luminous intensity and illuminance measurements are 0.41 % and 0.36 %, respectively. These uncertainties do not include the uncertainty components of the customer devices.

c) LMT photometer

A commercially available LMT photometer (LED-1, manufactured by Lichtmesstechnik GmbH) is used for luminous intensity measurements of LEDs. The photometer is cali-

[1] CIE Publication 127, “Measurement of LEDs”, (1997).

brated with a direct comparison against the reference photometer using a stable standard lamp as a light source. The expanded uncertainty ($k$ = 2) of illuminance measurement is 0.36 %.

### 2.4. Principle of the realization

The principle of the realization of luminous intensity and illuminance has been explained thoroughly in [2]. Therefore only a brief description is given here.

The luminous intensity of a light source is determined with a filter radiometer, which has a known absolute spectral responsivity. The wavelength dependence of the spectral responsivity of the filter radiometer is close to the $V(\lambda)$ curve [3]. A limiting aperture with a known area is used to define the solid angle over which light is collected. The filter radiometer and the limiting aperture form the reference photometer used as the primary standard. The structure of the filter radiometer is presented in Figure 1.

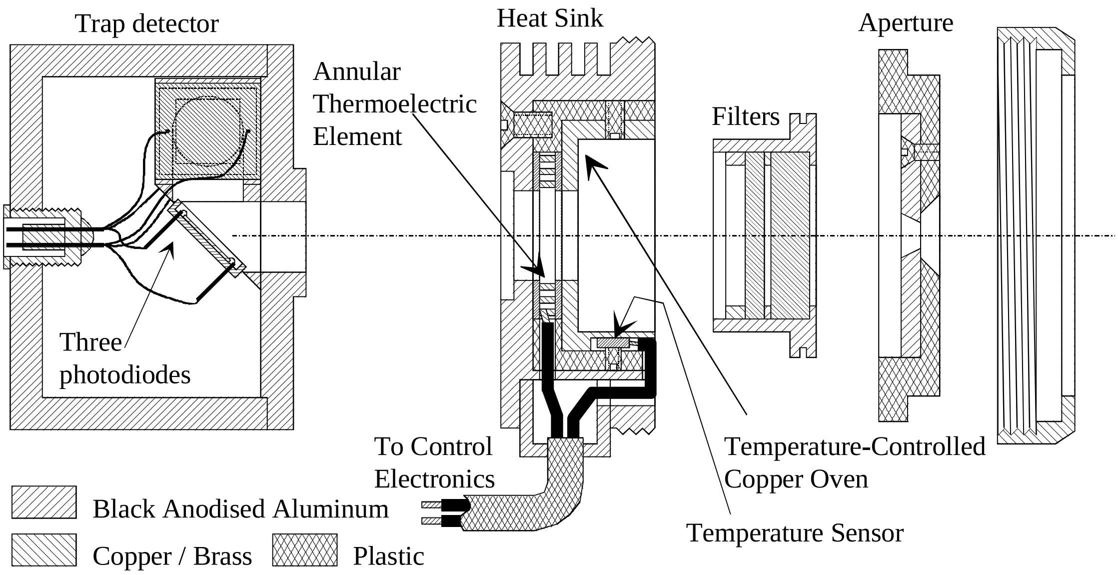


**Figure 1.** The structure of the filter radiometer.

The $V(\lambda)$ filter is assembled in an aluminium holder, which can also be used in the spectrometer during spectral transmittance measurements. The holder is placed into a heatsink which is attached to the trap detector. During luminous intensity measurements, the temperature of the filter is adjusted to 25.0 °C. The temperature of the filter is stabilized using a copper oven, whose temperature is measured by a temperature sensor and adjusted by a circular see-through Peltier element.

[2] Toivanen P., Kärhä P., Manoochehri F., Ikonen E., “Realization of the unit of luminous intensity at the HUT”, *Metrologia*, **37**, 131-140 (2000).

[3] CIE Publication 18.2, “The basis of physical photometry”, (1983).

The various components of the radiometer can be characterized separately, since the back reflection from the trap detector is weak. The photocurrent of the photometer is measured by a high accuracy current-to-voltage converter (CVC) and a digital voltmeter (DVM).

The luminous intensity $I_v$ of a light source is proportional to the measured photocurrent $i$ according to equation

$$I_v = \frac{K_m S_{eff}^{\ 2}}{A\, s(555\ \mathrm{nm})} F\, i\,, \tag{1}$$

where $K_m$ = 683 lm W$^{-1}$ is the maximum spectral luminous efficacy of radiation for photopic vision, $S_{eff}$ is the effective distance between the light source and the reference plane of the photometer, $A$ is the area of the limiting aperture, and s(555 nm) is the absolute responsivity of the photometer at the peak wavelength, 555 nm of the $V(\lambda)$-curve. The colour correction factor $F$ describes the effect of the difference between the theoretical $V(\lambda)$-curve and the relative spectral responsivity $s_{rel}(\lambda)$ of the photometer. It is calculated as a ratio of two integrals using

$$F = \frac{\int \Phi_e(\lambda) V(\lambda) \mathrm{d}\lambda}{\int \Phi_e(\lambda) s_{rel}(\lambda) \mathrm{d}\lambda}, \tag{2}$$

where $\Phi_e(\lambda)$ is the spectral radiant flux of the light source. For an ideal photometer, $F$ would be unity for any radiant source. In practice, the photometer is not ideal and the colour correction factor has to be used. Therefore, it has to be calculated separately for each combination of radiant source and photometer.

The relation between the photocurrent $i$ and the illuminance $E_v$ can be written as

$$E_v = \frac{K_m}{A\, s(555)} F\, i\,. \tag{3}$$

Photometers are usually calibrated for illuminance responsivity (A/lx). A stable reference source with a colour temperature close to that of the standard illuminant A (2856 K) is used as the light source.

# 3. Equipment

## 3.1. Description of setups

### 3.1.1. Equipment needed for reference photometer measurement

The equipment and accessories needed in the luminous intensity and illuminance measurements with the reference photometer are listed in Table 1.

Table 1. The equipment used in the measurements with the reference photometer.

| | Description | Quantity | Serial NR / Identification |
|---|---|---|---|
| A. | Photometer | | |
| 1. | Trap detector | 1 | FR-5 (spare item FR-8) |
| 2. | $V(\lambda)$-filter | 2 | cdf9502, cdf9401 |
| 3. | Temperature controlled filter holder | 1 | |
| 4. | Temperature controller electronics | 1 | Thorlabs |
| 5. | Aperture | 2 | NFRA1, HUT-7 (∅ 3 mm) |
| B. | Optical bench | | |
| 1. | Optical rail system (8 m) | 1 | R-1, Movetec Oy |
| 2. | Calibrated length scale | 1 | Calibration certificate: M-17L116 |
| 3. | Calibrated length block | 1 | Precalibrated or calibrated on-site using the rail system. |
| 4. | Stand for the photometer | 1 | |
| 5. | Carriage for the photometer | 1 | Part of rail system, Movetech Oy |
| 6. | Baffle frame | 1 | |
| 7. | Electronic shutter, adjustable aperture | 1 | Melles Griot 04-IES-215 ∅ 5–63 mm |
| 8. | Baffle adapter for shutter | 1 | BAS-1 |
| C. | Light sources | | |
| 1. | Osram Wi41/G | 5 | cds9501-9503,9904-9905 |
| 2. | Stand for the lamp | 1 | PRC Krochmann |
| 3. | Carriage for the lamp | 1 | Part of rail system, Movetech Oy |
| 4. | Osram FEL-S.T6 | 1 | BN-9101-391, BN-9101-465 |
| 5. | Lamp power supply | 1 | Heinzinger PTN55 125-10 |
| 6. | Standard resistor (100 mΩ) | 1 | Guildline 9230/15: 62587/SR96 |
| 7. | DVM | 1-2 | HP 3458A, HP 34401A, Agilent 34410A, Keysight 34461A |
| D. | Alignment system | | |
| 1. | Alignment laser | 1 | OMTec |
| 2. | Diffractive mirror | 1 | PRC Krochmann |
| 3. | Alignment jig | 1 | Gigahertz Optik |
| E. | Control and data acquisition | | |
| 1. | Computer | 1 | PC with access to MIKES-Aalto file system. |
| 2. | CVC | 1 | Lab Kinetics SP042 or MRI-CVC |
| 3. | DVM | 1 | HP 3458A |
| 4. | Software | 2 | Candela_TKK_v1_3.vi, Lux_TKK_v1_3.vi (or newer) |

### 3.1.2. Equipment needed for standard photometer measurement

The equipment and accessories needed in the luminous intensity and illuminance measurements with the standard photometers are listed in

Table **2**.

**Table 2.** The equipment used in the measurements with the standard photometers.

| | | Description | Quantity | Serial NR/ Identification |
|---|---|---|---|---|
| A. | Photometer | | | |
| | 1. | PRC or LMT photometer | 5 | 960319-1F / HUT-1,<br>960319-2F / HUT-2,<br>981129 / LM-1,<br>120318 / LM-2,<br>06A428 / LED-1 |
| | 2. | PSU of temperature controller | 4 | ± 15 V MRI-built power supply |
| B. | Optical bench | | | |
| | | As above | | |
| C. | Light sources | | | |
| | | As above | | |
| D. | Alignment system | | | |
| | | As above | | |
| E. | Control and data acquisition | | | |
| | 1.-2. | As above | | |
| | 3. | DVM | 1 | HP 3458A, HP 34401A, Agilent 34410A |
| | 4. | Software | 1 | Lux_customer.vi, |

## 3.2. Calibration requirements

### Maintenance of the equipment

To ensure accurate measurement results and traceability, the devices used in the calibrations must be calibrated often enough. The calibration schedule of the equipment is presented in Table 3. Due to the limited availability of new Wi41/G luminous intensity standard lamps, burning time of the lamps should be minimized. A practical method is to measure the luminous intensity and luminous flux standard lamps every other year or when needed. Calibration of illuminance responsivities of the reference photometer and the working standard photometers should be carried out annually.

**Table 3.** Calibration schedule of the calibration equipment.

| Device to be calibrated | Calibration interval [years] |
|---|---|
| $V(\lambda)$-filter transmittance | 1 |
| Trap detector responsivity | See Ref. 3. |
| Temperature controller electronics | 4 |
| Aperture area | 4 (checks with lamps every 2 years) |
| Length scale | 10 (mechanical check every 2 years) |
| Precision resistor | 4 |
| CVC | 2 |
| DVM | 3 |
| Temperature and humidity meter | 2 |
| Standard photometers | 1 |
| Luminous intensity standard lamps | 2 |

# 4. Measurement traceability

### Traceability chain of luminous intensity

The unit of luminous intensity, the candela, has been defined by the Conférence Générale des Poids et Mesures (CGPM). In 1979 it was redefined [4, 5] allowing any radiometric realization of the unit. In 2019 the definitions of kilogram, metre and second were updated, leading to a redefinition of the luminous intensity [6].

> *"The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540 × $10^{12}$ Hz, $K_{cd}$, to be 683 when expressed in the unit lm $W^{-1}$, which is equal to cd sr $W^{-1}$, or cd sr $kg^{-1}$ $m^{-2}$ $s^{3}$, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$."*

The frequency of 540 THz corresponds to a vacuum wavelength of 555.171 nm (555.016 nm in standard air at 20 °C), which is near the defined peak value of the spectral responsivity of the human eye.

The traceability chain of the luminous intensity scale is presented in Figure 2.

[4] Giacomo, P., "News from the BIPM", *Metrologia*, **16**, p.56 (1980).

[5] Giacomo, P., "News from the BIPM", *Metrologia*, **17**, p.74 (1981).

[6] BIPM, The International System of Units (SI), v1.06, p. 135, 9th edition (2019)

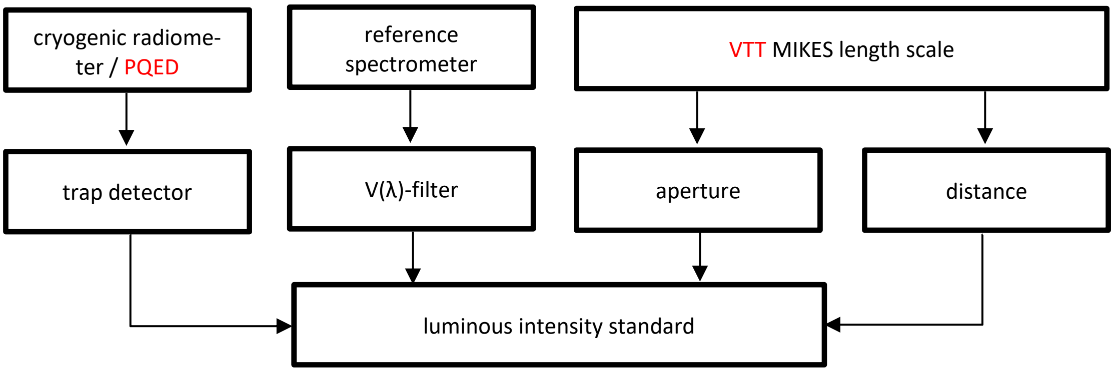


Figure 2. Traceability chain for the realization of the luminous intensity scale.

The luminous intensity standard has an unbroken chain of comparisons to the primary standards of optical power, spectral transmittance and length.

The various components of the radiometer can be characterized separately since the back reflection from the trap detector is weak. The absolute spectral responsivity of the trap detector is calibrated against the primary standard of optical power at a few laser wavelengths [7]. The absolute responsivity of the trap detector is obtained by a physical model for the external quantum efficiency of the photodiodes. The spectral transmittance of the $V(\lambda)$-filter is measured using the reference spectrometer [8]. The area of the aperture is measured by direct optical method [9] or alternatively by an optical coordinate measuring machine [10].

## 5. Calibration and measurement procedures including validation methods

A typical luminous intensity measurement setup is shown in Figure 3, with one circular baffle between the source and the reference photometer. The lamp current is monitored by using a single value precision resistor and a DVM. The voltage across the lamp terminals is measured using an additional DVM (4-terminal measurement). Alternatively, if only one DVM is used, an additional pair of wires is connected to the rear terminal of the DVM. The photocurrent of the photometer is measured using a CVC and a DVM.

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[7] Quality manual of optical power laboratory.

[8] Quality manual of reference spectrometer laboratory.

[9] Ikonen E., Toivanen P., Lassila A., "A new optical method for high-accuracy determination of aperture area", *Metrologia*, **35**, 369-372, (1998).

[10] B. Hemming, E. Ikonen, and M. Noorma, "Measurement of aperture diameters using an optical coordinate measuring machine," *Int. J. Optomechatronics* **1**, 297–311 (2007).

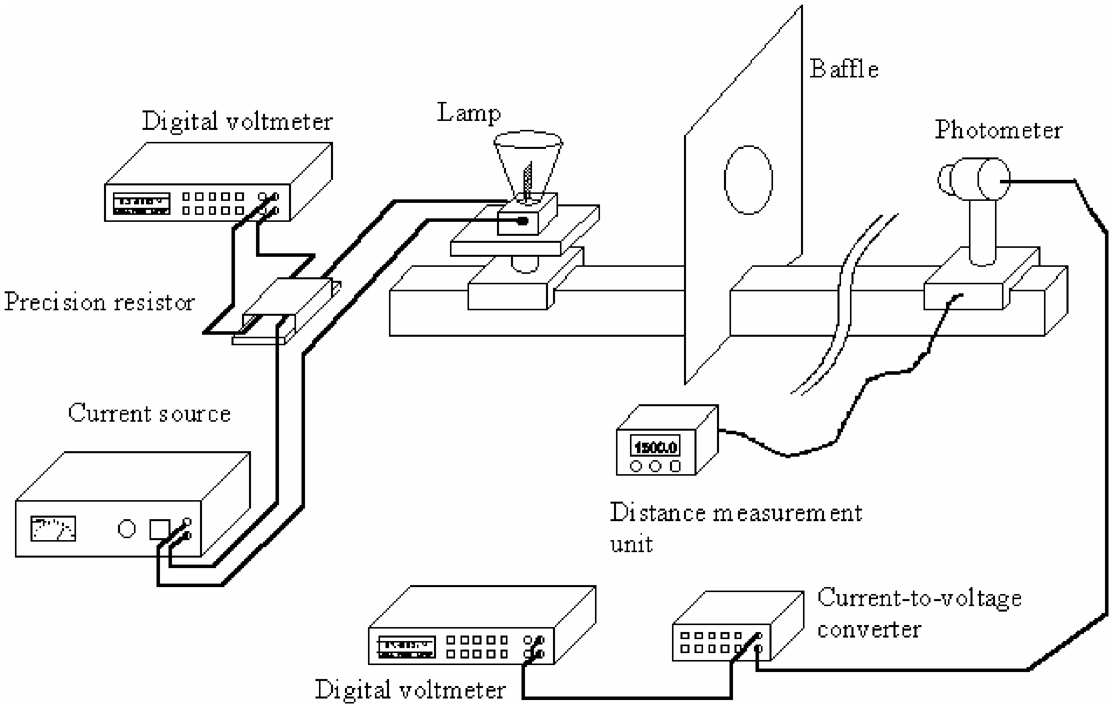


**Figure 3.** A typical luminous intensity measurement setup.

The photometer and the baffle are placed on the 8-meter optical rail equipped with a calibrated length scale. The optical rail is housed in a light-tight enclosure. The enclosure is made of black anodized aluminum plates.

The optical axis of the bench is determined with a two-beam alignment laser (OMTec) positioned between the detector and the lamp. The beam is directed along the rail by aiming it through the center of the baffle(s) to the alignment targets on the opposite sides of the rail system.

### 5.1. Measurement procedure for luminous intensity standard lamps

Calibration of the luminous intensity of 100 – 1000 W incandescent standard lamps is performed every two years. The corresponding luminous intensities are approximately 250 – 1000 cd. Measurement program Candela_TKK.vi is in the measurement computer (see Table 1) in directory:

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#### 5.1.1. Lamp alignment

Lamp alignment procedures are described in [11].

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[11] Instruction manual for operating standard lamps.

### 5.1.2. Detector alignment and initial distance

The detector is aligned with the laser beam so that the back-reflection from the first surface of the $V(\lambda)$-filter is directed through the alignment laser to the centre of the lamp target within a full-cone angle of 0.05° with respect to the original beam. If the detector does not have a back-reflection, i.e. in the case of a detector with a diffuser input, an alignment mirror can be used in front of the diffuser.

The distance between the detector and the lamp is measured from the filament plane of the lamp to the aperture plane of the detector. Even though the exact position of the filament is known, the glass envelope of the lamp acts as refracting material and the effective position of the filament may have some apparent shift along the optical axis. The longer the distance between the source and the detector, the less relative error is introduced by the constant distance setting error and the refraction of the lamp envelope.

More accurate effective distance between the lamp filament and the aperture plane can be calculated by applying an inverse square law to the measurement results. For the reason that the detector carrier may not be able to move close enough to the lamp for distance measurement, a relatively short calibrated piece of metal is placed between the front surfaces of the diffractive mirror and the photometer[*]. The length of the metal block *x* can be calibrated using the calibrated 8-m optical rail system. The distance measuring unit is reset and the carrier is moved away from the lamp to reach the initial measurement position. Now the effective distance between the filament and the aperture plane of the photometer is

$$S_{\mathrm{eff}} = d + x + s + 3\ \mathrm{mm}, \qquad (4)$$

where *d* is the unknown *distance offset* between the reference surface of the lamp and the lamp filament. The aperture plane of the photometer is 3 mm behind the front surface and needs to be taken into account in the distance calculations. In the measurement data analysis, the distance offset is chosen so that the luminous intensity calculated from Eq. 1 remains constant. Suitable initial measurement distance is about 500 mm.

### 5.1.3. Baffles

A baffle with an electronic shutter and an adjustable aperture is placed between the lamp and the detector to reduce straylight and reflections from the cabinet and the rail. The baffle is positioned about 30 cm in front of the filament plane of the lamp. A suitable opening of the aperture is about 50 mm in diameter. The light emitted backwards by the lamp is absorbed using absorbing material on the wall behind the lamp. An additional baffle with an opening of 10 cm is used between the first baffle and the detector when

[*] This method can be applied only if the lamp has a well-established reference surface (diffractive alignment mirror, front surface of the lamp base etc.) For other types of lamps see Section 5.1.5.

the measurement distance is long. More information about using baffles can be found in [11].

#### 5.1.4. Measurement

The photocurrent of the photometer is measured with a CVC and a DVM. The sensitivity setting of the CVC is checked before each measurement point. The sensitivity should be selected in such a way that the output voltage of the CVC is in the range of 0.5 – 5.0 V for maximum linearity. The preamp of the CVC should be used at the unity gain ($G$ = -1). If the CVC has a built-in low-pass filter, it can be used for reducing noise. The DVM is used with an integration time of 2 seconds (NPLC = 100). The default calibration of luminous intensity takes approximately 20 minutes to complete and includes illuminance measurements at positions ($s$ + $d$) = 500, 1000, 1500, 2000 and 2500 mm.

Each illuminance measurement includes 30 samples (sequence: 10x dark current, 20x illuminance current). The dark current of the photometer is measured by blocking the light source before each illuminance measurement. The average of these measurement values is used as the dark current.

The measured data is automatically analyzed with the LabVIEW measurement file Candela_TKK.vi.

#### 5.1.5. Measuring lamps without fixed reference surface

Customer luminous intensity standard lamps with flat filaments may not have a fixed reference surface or an alignment mirror. This means that the lamp needs to be aligned using a telescope. The principle of the alignment is presented in Figure 4.

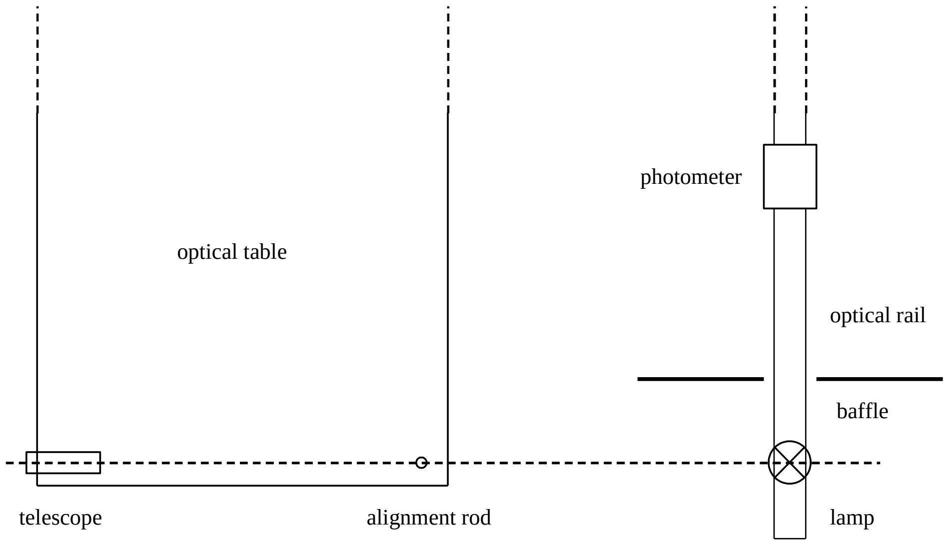


Figure 4. Alignment of the lamp with a telescope. When using the 8-m rail of the photometry laboratory, a tripod should be used for mounting the telescope instead of an optical table.

The telescope is mounted on a tripod next to the optical rail so that the lamp can be seen when looking through the telescope; the lamp is moved if necessary. The lamp is moved out of the way, and a photometer that has been aligned using a procedure described above is moved in its place. The telescope is moved and rotated until the front surface of the photometer appears as a single line (i.e., the visible area of photometer front surface is minimized) at the center of view of the telescope. The telescope is now aligned perpendicular to the optical axis. The distance reading is zeroed, and the photometer is moved away. The lamp is moved and rotated until the area of the filament seen through the telescope is minimized and at the center of the view of the telescope.

The measurement procedure is similar to that described in Section 5.1.2. Five illuminance values are measured at 500 mm intervals, but the initial distance is unknown. Effective distances and the luminous intensity of the lamp are determined by applying the inverse square law fitting to the measured illuminance values.

## 5.2. Measurement procedure for standard photometers

Standard photometers (PRC and LMT) are calibrated by direct substitution against the primary standard. As a light source, a stable standard lamp is used at a colour temperature close to that of the standard illuminant A (2856 K). Typically the standard lamp cds9905 is used as a working standard. The alignment procedures for the lamp and the photometers are the same as in sections 5.1.1. and 5.1.2.

The calibration is conducted by measuring the illuminance with the reference photometer and the standard photometers at a distance of 2.5 m from the lamp. The secondary circular baffle having a 100 mm diameter is set in midway of the measurement distance to reduce reflections from the measurement rail. The reference plane of the photometer is either its aperture plane, 3 mm behind the front surface (HUT-1, HUT-2, LED-1) or the front surface of the flat diffuser (LM-1, LM-2). Measurement program Lux_TKK.vi is in the measurement computer (see Table 1) in the directory:

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The measurement data is automatically analyzed with this LabVIEW program.

## 5.3. Measurement procedure for customer illuminance meters

Customer photometers (illuminance meters) are calibrated by direct substitution against the PRC photometer HUT-2. The initial reference plane of the customer photometer (typically the diffuser plane) is set to the same distance as the reference plane of the PRC photometer.

Since the true distance reference plane of a thick or a dome-shaped diffuser is most likely inside the diffuser [12], the distance offset of such diffuser needs to be determined. The relative measurement distances for each illuminance value are written down. Analysis takes place according to [12].

As a light source, a stable standard lamp is used at a colour temperature close to that of the standard illuminant A (2856 K). For calibrations over a wide range of illuminance levels, lamps of different power levels are needed. The illuminance ranges of the reference lamps used in customer calibrations are presented in Table 4. The range is defined by approximate illuminance levels at $S_{\mathrm{eff}}$ = 500 mm and 7000 mm.

Table 4. Approximate illuminance ranges and currents using different types of light sources.

| Light source | Osram Wi41/G cds9905 | Osram Sylvania T6 FEL-391 | Osram Sylvania T6 FEL-391 & Diffuser |
|---|---|---|---|
| Current [A] | 5.9200 | 7.1700 | > 7.17 A (Adjust) |
| Illuminance range [lx] | 5 – 1100 | 25 – 5000 | 0.1 – 15 |

Above 300 lx, the 1 kW Osram Sylvania T6 (serial number BN-9101-391) should be used. More information about this type of lamp is found in [11]. At lowest illuminance ranges the BN-9101-391 lamp is operated with a diffuser assembly consisting of a glass diffuser and two apertures (Figure 5). The diffuser assembly effectively forms a new light source with lower luminous intensity. The assembly should be placed in front of the lamp in such a way that the diffuser element is towards to the lamp, and the baffle of the assembly touches the aperture assembly of the rail baffle. The lamp current needs to be increased to compensate for the spectral transmittance of the diffuser in order to achieve correlated colour temperature close to that of the standard illuminant A. The CCT of the diffuser source can be checked with the Konica Minolta CS-2000A spectroradiometer.

The measurement procedure depends on the customer needs and therefore it is not fixed. The measurement program **Lux_customer.vi** is in the measurement computer (see Table 1) in directory

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

[12] J. Hovila, M. Mustonen, P. Kärhä, E. Ikonen, "Determination of the diffuser reference plane for accurate illuminance responsivity calibrations," *Applied Optics* **44**, 5894-5899 (2005).

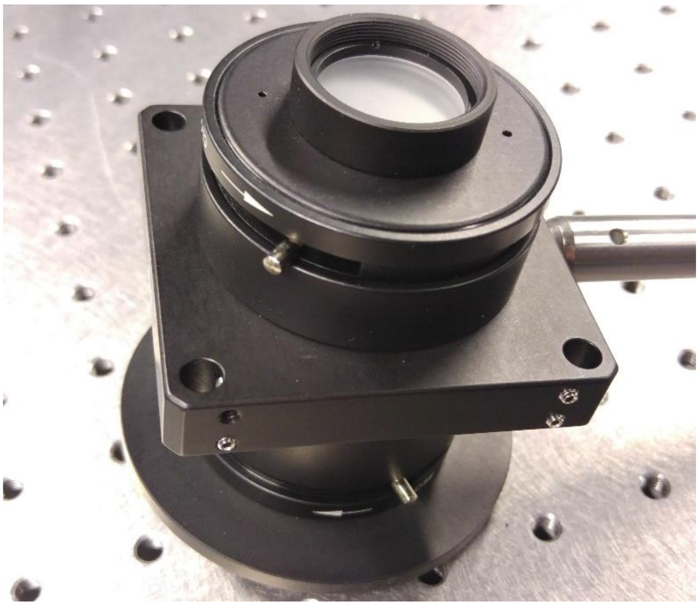

Figure 5: Diffuser assembly used with FEL lamps at low illuminance levels.

# 6. Handling of calibration items

## 6.1. Precautions

Reference lamps sent for calibration are expensive equipment and deserve the outmost care in handling and use. The lamps must be kept clean and mechanical shocks should be avoided. Precautions are presented in the following list:

- The lamps should be turned on and off slowly (30–60 seconds). The lamps should not be moved while operated.
- In order to prolong the useful lifetime of the lamps, it is recommended that they are used sparingly and great care should be taken so that at no time the current will exceed the allowed value.
- Photometric measurements should be made only after the lamp has stabilized (at least 15 minutes after ignition).
- Assure that the lamp area has good ventilation around it. Poor ventilation leads to excessive noise in the measurement.
- The glass envelope of the lamp must not be touched by bare fingers, nor with gloves. Hold the lamp at the socket. If there is grease or dirt on the envelope do not try to clean it.

### 6.2. Monitoring of lamps and photometers

In order to notice when a standard lamp or a photometer is no longer working properly, their characteristics must be monitored regularly. The calibration interval for the luminous intensity standard lamps and standard photometers can be found in Table 3. In the meantime, recalibration should take place if necessary.

The usage of each lamp is monitored by using a logbook, "Photometry, Log Book of Lamps". The logbook is kept in the photometry laboratory, next to the standard lamps. Every time a lamp is operated, the following data is written down: date, lamp burn time (on / off / total), current, voltage (begin / end) and the user's initials.

The history of the MRI luminous intensity standard lamps is presented in Table 5. The corresponding lamp currents, base voltages and distance offsets are also stated. A sudden change in the base voltage indicates that something has happened to the lamp filament. Therefore, the lamp should be taken through further inspection.

The measured illuminance responsivity values for the standard photometers are presented in

Table **6**. Absence of HUT-1 data is due to $V(\lambda)$ filter replacement in 2004.

Table 5. Luminous intensity standard lamps and their characteristics.

| LAMP | cds9501* | cds9502 | cds9503 | cds9904 | cds9905* | FEL391* | FEL465* |
|---|---|---|---|---|---|---|---|
| Current [A] | 5.9420 | 5.8732 | 5.9103 | 5.8245 | 5.8201 | 7.0200 | 7.3380 |
| Voltage [V] | 30.452 | 31.055 | 30.912 | 29.652 | 29.840 | 84.904 | 87.725 |
| Colour temperature [K] | 2856 | 2843 | 2846 | 2857 | 2857 | 2855 | 2859 |
| Offset *d* [mm] | 81.3 | 80.2 | 84.1 | 82.5 | 81.4 | 25.9 | 25.9 |
| Date | Luminous intensity [cd] | | | | | | |
| 15.9.1998 | | 287.20 | | | | | |
| 9.3.1999 | 292.43 | | | | | | |
| 24.11.1999 | | | 288.11 | | | | |
| 9.2.2000 | 293.01 | | | | | | |
| 22.3.2000 | 289.02 | 286.14 | 288.38 | 262.46 | 264.36 | | |
| 9.1.2001 | 289.72 | 286.67 | 288.25 | | | | |
| 17.1.2001 | 289.49 | 286.64 | 287.86 | | | | |
| 9.-11.1.2002 | 289.25 | 285.74 | 288.04 | 263.14 | 265.44 | | |
| 20.-22.1.2003 | 288.87 | 286.84 | 288.93 | 263.87 | 267.04 | | |
| 23.1.2003 | 310.04 | | | | 298.82 | | |
| 19.-20.1.2004 | 297.59 | 285.46 | 284.05 | 262.51 | 296.57 | | |
| 22.3.-4.4.2005 | 279.13 | 285.26 | 284.81 | 261.72 | 268.66 | 871.16 | |
| 28.3.-1.9.2006 | 292.72 | 284.27 | 283.60 | 260.75 | 267.80 | 869.56 | |
| 25.4.2008 | 304.80 | 283.24 | 282.56 | 260.68 | 264.92 | 947.86 | |
| 12.1.-6.2.2009 | | 282.95 | 280.24 | 259.67 | 266.29 | | |
| 4.6.-8.6.2010 | | 282.43 | 279.79 | 259.94 | 265.67 | | |
| 13.3.-14.3.2012 | | 284.12 | 281.42 | 260.89 | 265.17 | | |
| 3.4.-11.4.2013 | | 283.98 | 281.18 | 260.91 | 262.92 | | |
| 10.6-11.6.2015 | | 284.25 | 281.29 | 261.75 | 262.41 | | |
| 25.5.-28.5.2018 | | 283.92 | 280.88 | 261.33 | 259.55 | | |

* Lamps cds9501, cds9905, FEL-391 and FEL-465 are used for customer luxmeter calibrations and their currents are adjusted to obtain CCT close to 2856 K. Lamp currents may change every year in order to maintain the correct CCT. This leads to deviations in the luminous intensity values.

Table 6. Characteristics of the secondary illuminance standard photometers.

| Photometer | HUT-1 (960319-1F) | HUT-2 (960319-2F) | LM-1 (981129) | LM-2 (120318) | LED-1 (06A428) |
|---|---|---|---|---|---|
| Date | Illuminance responsivity [nA/lx] | | | | |
| 27.5.1996 | - | 12.118 | | | |
| 27.6.1996 | - | 12.125 | | | |
| 26.7.1996 | - | 12.121 | | | |
| 17.12.1996 | - | 12.160 | | | |
| 27.1.1997 | - | 12.176 | | | |
| 12.2.1997 | - | 12.169 | | | |
| 20.2.1997 | - | 12.157 | | | |
| 23.2.1997 | - | 12.149 | | | |
| 16.5.1997 | - | 12.137 | | | |
| 19.5.1997 | - | 12.134 | | | |
| 19.5.1997 | - | 12.135 | | | |
| 28.1.1998 | - | 12.151 | | | |
| 9.3.1999 | - | 12.150 | 1.631 | | |
| 7.6.2000 | - | 12.150 | - | | |
| 9.1.2002 | - | 12.132 | - | | |
| 20.1.2003 | - | 12.097 | 1.656 | | |
| 12.9.2003 | - | 12.141 | - | | |
| 10.2.2004 | - | 12.158 | 1.661 | | |
| 4.4.2005 | 12.864 | 12.161 | 1.658 | | 2.616 |
| 28.3.2006 | 12.881 | 12.184 | 1.610 | | 2.616 |
| 28.5.2007 | 12.858 | 12.160 | 1.607 | | 2.609 |
| 21.2.2008 | 12.880 | 12.192 | 1.599 | | 2.608 |
| 20.2.2009 | 12.882 | 12.179 | - | | 2.605 |
| 9.6.2010 | 12.893 | 12.200 | 1.577 | | 2.600 |
| 10.5.2011 | 12.876 | 12.166 | - | | - |
| 23.2.2012 | 12.858 | 12.164 | 1.560 | | 2.593 |
| 22.3.2013 | 12.830 | 12.140 | 1.529 | 1.194 | 2.583 |
| 27.3.2014 | 12.812 | 12.132 | 1.482 | 1.192 | 2.580 |
| 24.4.2015 | 12.828 | 12.154 | 1.474 | 1.195 | 2.586 |
| 22.4.2016 | 12.826 | 12.154 | 1.473 | 1.198 | 2.586 |
| 2.6.2017 | 12.854 | 12.182 | 1.480 | 1.199 | 2.579 |
| 25.5.2018 | 12.852 | 12.181 | 1.474 | 1.203 | 2.579 |
| 9.4.2019 | 12.779 | 12.130 | 1.470 | 1.198 | 2.560 |
| 18.5.2020 | 12.803 | 12.115 | 1.469 | 1.202 | 2.566 |

# 7. Uncertainty budgets

The uncertainty budgets for luminous intensity and illuminance measurements using reference photometer are presented in Table 7. More detailed information about the uncertainty budgets can be found in [2].

**Table 7.** Uncertainty budgets of luminous intensity and illuminance measurements.

| | $10^4 \times$ relative standard uncertainty | |
|---|---|---|
| Component | Luminous intensity | Illuminance |
| *Detector* | | |
| Absolute responsivity | 7.8 | 7.8 |
| Non-linearity | 1.2 | 1.2 |
| Spatial non-uniformity | 0.5 | 0.5 |
| Photocurrent measurement | 1.0 | 1.0 |
| *Filter* | | |
| Peak transmittance | 10.0 | 10.0 |
| Spatial non-uniformity | 4.4 | 4.4 |
| Angular dependence of transmittance | 0.5 | 0.5 |
| Temperature setting | 1.7 | 1.7 |
| Polarization dependence of transmittance | 0.6 | 0.6 |
| Out-of-band leakage | 2.0 | 2.0 |
| *Color correction factor* | | |
| Spectral responsivity of trap detector | 1.0 | 1.0 |
| Spectral transmittance of filter | 2.1 | 2.1 |
| Angular dependence of spectral transmittance | 0.7 | 0.7 |
| Temperature dependence of spectral transmit- | 0.3 | 0.3 |
| Spectrum of lamp | 0.5 | 0.5 |
| *Aperture area* | 4.0 | 4.0 |
| *Interreflections in the photometer* | 0.9 | 0.9 |
| *Measurement related* | | |
| Operating current of the lamp | 3.2 | 0.5 |
| Distance measurement (2600 mm) | 8.0 | 1.7 |
| Thermal expansion of the optical rail (±2.5 °C)* | 0.2 | 0.2 |
| Stray light | 2.0 | 0.9 |
| Repeatability of the alignment | 4.0 | 0.5 |
| Diffraction | 0.7 | 0.7 |
| Combined standard uncertainty | 18 | 15 |
| Expanded uncertainty ($k$ = 2) | 36 | 31 |

* Using the thermal expansion coefficient of aluminium ($23.1\times10^{-6}$ $K^{-1}$), and assuming uniform temperature distribution in the ±2.5 °C region, the uncertainty component would be $0.07\times10^{-4}$. A higher uncertainty is given due to unknown temperature coefficients of optical rail system.

When using the standard photometers, the measurement uncertainty increases due to the unit transfer from the reference photometer. The additional relative standard uncertainty contribution is 0.1 %. The overall expanded uncertainty ($k$ = 2) is therefore 0.41 % for the luminous intensity calibrations and 0.36 % for the illuminance calibrations.

# 8. Accommodation and environmental conditions

The photometry laboratory is the room 1559 located in the first floor of Maarintie 8 building. Instructions for using the clean rooms have been given in [13].

When not in use, the detectors and filters are stored in a dry cabinet which is located in the irradiance laboratory (1567). The photometers can be stored assembled in the cabinet, to make calibration preparations easier. During luminous intensity and illuminance calibrations, the temperature and humidity levels should be monitored. The clean zone air filter should be on to filter the dust from the air. [11]

# 9. Field calibrations

Field calibrations may be done for certain customers. Care should be taken when transporting laboratory equipment to customer premises. Quality assurance routines and operating instructions of the customers are to be followed. This concerns e.g.

- Operation of the customer equipment.
- Control and monitoring of environmental conditions.
- Alignment and distance measuring.

The procedures used should be recorded to the calibration setups with care, and the effect of deviations should be estimated and added to the uncertainty budgets.

# 10. Measurement data

The measurement data coming from the calibrations and development of equipment are archived.

~~*Measurements performed by P. Toivanen:*~~

~~The measurement notes (date, set-up, raw data) are written down in a blue map “Candela Measurement Notes”. The analyzed measurement data are stored in chronological order in a blue file “Candela Measurement Data”. The related computer data files are also stored in the latter map.~~

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[13] Clean room instructions / Puhdastilaohjeet.

~~*Measurements performed by J. Hovila:*~~

~~The measurement notes (date, set-up, raw data) are written down in a brown map "Photometric Measurements and Calibrations". 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.~~

~~*Measurements performed by P. Manninen:*~~

~~The electrical data are stored in file /Kalibrointi ja ylläpito/. There are two sub directories for /Customers/ -calibrations and /MRI references/ -calibrations.~~

*Measurements performed by T. Poikonen:*

The electrical data are stored in file \MIKES-Aalto\Users\Z Old Personnel\Tuomas Poikonen\CALIBRATION\Optical (T-R). Measurement reports on paper are stored in file labeled "Omat kalibroinnit, Tuomas Poikonen, MIKES TKK Mittaustekniikka".

*Measurements performed by J-M. Hirvonen:*

The electrical data are stored in file \MIKES-Aalto\Users\Z Old Personnel\Juha-Matti Hirvonen\Kalibroinnit.

*Measurements performed by H. Baumgartner:*

The electrical data are stored in file \MIKES-Aalto\Users\Z Old Personnel\Hans Baumgartner\calibs.

*Measurements performed by T. Pulli:*

The electrical data are stored in file \MIKES-Aalto\Users\Z Old Personnel\Tomi Pulli\CALIBRATIONS.

*Measurements performed by J. Askola:*

The electrical data are stored in file \MIKES-Aalto\Users\Janne Askola\CALIBRATIONS.

*Measurements performed by V. Mantela:*

The electrical data are stored in file \MIKES-Aalto\Users\Ville Mantela\CALIBRATIONS.

## 11. Certificates

Calibration certificates are handled according to [14]. Include in the calibration certificate:

- Ambient temperature and relative humidity

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

- Current, voltage, luminous intensity and the distance offset of the lamp (luminous intensity calibration)
- Reference values and measured values with corresponding correction factors (illuminance calibration)
- Distance offset of the diffuser (if any)

## 12. Intercomparisons

The latest international comparisons of the units of luminous intensity and illuminance (luminous) responsivity:

- 1997: Comparison of luminous intensity units with NPL (UK) [15]

  Level of agreement 0.27 % with an expanded uncertainty (*k* = 2) of 0.56 %.

- 1998: Key comparison CCPR-K3.b of luminous responsivity [16]

  Level of agreement 0.32 % with an expanded uncertainty (*k* = 2) of 0.60 %.

- 2000: Comparison of illuminance responsivity units with NIST (USA) [17]

  Level of agreement 0.08 % with an expanded uncertainty (*k* = 2) of 0.47 %.

- 2004: Comparison of illuminance responsivity units with KRISS (Korea) [18]
- 2008: Luminous Intensity EURAMET.PR-K3a Key-Comparison [19]

  Level of agreement 0.32 % with an expanded uncertainty (*k* = 2) of 0.44 %.

- 2018: Comparison of luminous intensity sources based on LEDs in EMPIR PhotoLED project [20]

  The measurement results of Aalto were on average 0.79% higher than the ones of the pilot.

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[15] Goodman T. M., Toivanen P., Nyberg H., Ikonen E., "International comparison of luminous intensity units between the NPL (UK) and the HUT (Finland)", *Metrologia*, **36**, 15-18 (1999).

[16] Köhler R., Stock M., Carreau C., "Final Report on the International Comparison of Luminous Responsivity CCPR-K3.b", Bureau International des Poids et Mesures, (2001). http://www.bipm.fr/kcdb

[17] 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).

[18] E. Ikonen, J. Hovila, "Final Report of CCPR-K3.b.2-2004: Bilateral comparison of illuminance responsivity scales between the KRISS (Korea) and the HUT (Finland)," *Metrologia* **41**, *Technical Supplement*, 02003 (2004).

[19] A. Sperling, G. Sauter, D. Lindner and M. Eltmann, "Final report on regional comparison EURAMET.PR-K3.a: Luminous intensity," Metrologia 51 02001, 2014.

[20] T. Gerloff et. al., "Luminous intensity comparison based on new standard lamps with LED reference spectrum," in Proceedings of the 29th CIE Session. pp. 77-84, CIE Quadrennial Session, Washington, United States, 2019.

# 13. Publications

[21] Manninen P. "*Characterization of diffusers and light-emitting diodes using radio metric measurements and mathematical modelling*," Doctoral thesis, Helsinki University of Technology, Espoo, Finland, 67 p (2008).

[22] Poikonen T., Kärhä P., Manninen P., Manoocheri F., and Ikonen E., "*Uncertainty Analysis of Photometer Quality Factor $f_1'$*," *Metrologia* **46**, 75–80 (2009).

[23] Poikonen T., Blattner P., Kärhä P., and Ikonen E., "*Uncertainty Analysis of Pho tometer Directional Response Index $f_2$ using Monte Carlo Simulation*," *Metrologia* **49**, 727–736 (2012).

[24] Poikonen T. "*Characterization of light emitting diodes and photometer quality factors*," Doctoral thesis, Aalto University, Espoo, Finland, 92 p (2012).