metrologia

Realizations of the units of luminance and spectral radiance at the HUT

P. Toivanen, J. Hovila, P. Kärhä and E. Ikonen

Abstract. Realizations of the units of luminance and spectral radiance at the Helsinki University of Technology (HUT) are presented. These realizations are linked to HUT units of luminous intensity and spectral irradiance using a characterized photometer, a spectroradiometer and an integrating-sphere light source. A new method for determining the spatial uniformity of the output of the integrating-sphere source is described. The uncertainty analysis indicates a relative expanded uncertainty of 3.6×10^{-3} (coverage factor $k = 2$) for the realization of the unit of luminance. The expanded uncertainty for the realization of the unit of spectral radiance varies between 6×10^{-3} and 2.5×10^{-2} in the wavelength region 360 nm to 830 nm.

1. Introduction

Luminance is a photometric quantity that describes the brightness of a surface. A detector-based realization of the unit of luminance has recently been presented [1], based on an integrating-sphere light source, the luminous intensity of which is measured by a characterized photometer. The luminance value at the aperture plane of the integrating sphere is obtained from the measured luminous-intensity value. In addition, the area of the output aperture of the sphere has to be known.

In this paper, we present our realization of the units of luminance and spectral radiance. These realizations are linked to HUT units of luminous intensity and spectral irradiance using an integrating-sphere light source and a spectroradiometer. The method for the realization of the unit of luminance is comparable to that described in [1]. The unit of spectral radiance is realized by measuring the relative spectral irradiance of the light source. The spectral radiance at the aperture plane of the integrating sphere is then calculated from the measured luminance and the relative spectral irradiance values. We have developed a new method for characterizing spatial non-uniformity, which is one of the largest uncertainty components of the output of the integrating-sphere source.

2. Measurement set-up and realization of units

2.1 Measurement set-up

The measurement set-up consists of a photometer, a spectroradiometer, an integrating-sphere light source, and an optical bench. During the measurements, the integrating sphere, the photometer, and the measuring head of the spectroradiometer are placed on the optical bench as shown in Figure 1. The measuring head of the spectroradiometer is installed on a magnetic base, with which it can be easily removed and reinstalled without affecting the alignment. When the photometer is used, the measuring head is removed. The optical axis is determined by a laser unit with two beams propagating in opposite directions. A mirror is temporarily attached to the aperture of the integrating-sphere source and another is attached to the measuring head of the spectroradiometer. The photometer, the measuring head, and the integrating-sphere light source are aligned using the back-reflections from the mirrors or the filter of the photometer. After alignment, the laser unit is removed. The optical bench is covered with a light-tight aluminium box. A baffle is placed between the light source and the photometer or the measuring head.

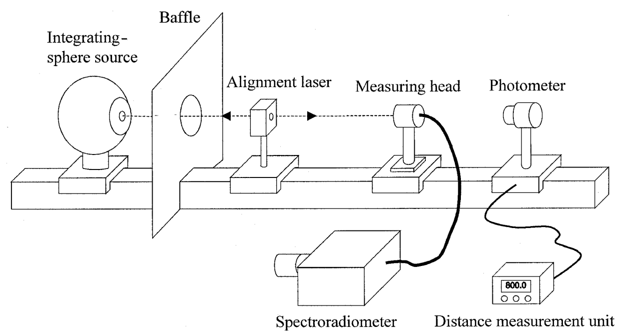

Figure 1. Principle of the measurement set-up for realization of the units of luminance and spectral radiance.

The luminous responsivity of the photometer is traceable to our realization of the unit of illuminance [2]. The diameter of the aperture of the photometer is 8 mm. The photocurrent of the photometer is measured using a high-precision current-to-voltage converter and a digital voltmeter.

The spectroradiometer, a double-grating monochromator with a photomultiplier tube, has a usable wavelength range from 250 nm to 845 nm, although only the visible wavelength region is covered by

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the measurements in this report. The bandwidth of the monochromator is 1 nm. The measuring head, consisting of a Teflon diffuser and an entrance aperture, is connected to the input of the monochromator by an optical fibre. The spectral irradiance responsivity of the spectroradiometer is traceable to the HUT unit of spectral irradiance [3].

The diameter of the integrating sphere is 12 inches (30.48 cm). The integrating sphere, which is coated with barium sulphate paint, is illuminated by two tungsten-halogen lamps. The lamps utilize dichroic back-reflectors to reduce heat in the sphere. The luminous flux in the sphere can be tuned by iris diaphragms between the lamps and the sphere. The operating current of the lamps has been chosen in such a way that the correlated colour temperature of the source is 2856 K at the maximum luminance level of 40 000 cd/m^2. Owing to the spectral selectivity of the dichroic reflectors behind the lamps, the correlated colour temperature increases when the luminance level is decreased. At the minimum luminance level of 250 cd/m^2, the correlated colour temperature is 2870 K.

The output port of the integrating sphere is limited by a high-precision aperture. Black-anodized aluminium apertures with diameters of 8 mm and 16 mm are used. The inner walls of the apertures are cut at an angle of 45° to produce a sharp edge. The diameters of the apertures are measured in 40° steps using a line-scale interferometer with a microscope and a charge-coupled-device camera for edge detection.

The distances between the aperture plane of the integrating-sphere source and the photometer, or the measuring head of the spectroradiometer, are measured by a magnetic length scale [2]. At the beginning of the measurements, the photometer or the measuring head is placed in contact with the aperture holder of the integrating-sphere source. The measuring head or the photometer is then moved to the appropriate measurement distance, determined using the length scale. The distance between the front surface of the aperture holder and the aperture plane of the integrating-sphere source is measured mechanically.

2.2 Luminance calibration

Luminance is defined as the luminous intensity per unit area. Therefore, the average luminance L_v over the area A of the output of the integrating-sphere source may be obtained as

$$L_\mathrm{v} = E_\mathrm{v} D^2 / A, \tag{1}$$

where E_v is the illuminance at the effective distance D between the aperture plane of the source and the photometer. The effective distance depends on the radius of the limiting aperture r_1, the radius of the source r_2, and the physical distance d between the source and the aperture according to the relation [4]

$$D^2 = r_1^2 + r_2^2 + d^2. \tag{2}$$

Equation (2) is accurate to better than 1 part in 10^4 for distances that are more than one decade greater than the radii.

The illuminance is measured at a distance of 800 mm. The luminous intensity of the source is determined only at the maximum luminance level. The lower luminance levels are determined by measuring relative changes in illuminance, with the photometer placed close to the aperture plane of the integrating sphere.

2.3 Spectral radiance calibration

Spectral radiance $L_\mathrm{e}(\lambda)$ is the radiometric quantity corresponding to the luminance L_v. Spectral radiance and luminance are linked by

$$L_\mathrm{v} = K_\mathrm{m} \int_{360\ \mathrm{nm}}^{830\ \mathrm{nm}} L_\mathrm{e}(\lambda) V(\lambda) \mathrm{d}\lambda, \tag{3}$$

where $V(\lambda)$ is the spectral luminous efficiency function for photopic vision and $K_\mathrm{m} = 683$ lm/W is the proportionality constant between the watt and the lumen in the definition of the candela.

Spectral radiance is determined in our set-up by measuring the luminance $(L_\mathrm{v,m})$ and the relative spectrum of the output of the integrating-sphere source. The spectroradiometer is used to measure the spectrum at a distance of 100 mm. A luminance value $(L_\mathrm{v,c})$ is calculated by (3) with the measured spectrum, and a normalization factor $k = L_\mathrm{v,m}/L_\mathrm{v,c}$ is determined. Spectral radiance is then obtained by multiplying each spectral component by the normalization factor.

3. Uncertainty analysis

Table 1 presents the results of the uncertainty analyses for the realizations of the units of luminance and spectral radiance. All known uncertainty components are included, whether significant or not. The uncertainty of spectral radiance has to be calculated separately for each wavelength. For simplicity, the uncertainty budget is presented only at a wavelength of 600 nm. Figure 2 gives the combined standard uncertainty as a function of wavelength. Detailed uncertainty analyses for the realizations of the units of illuminance and spectral irradiance may be found in [2, 3], respectively.

3.1 Uncertainty components relating to integrating-sphere source

The stated uncertainty value of the aperture area contains components arising from the uncertainty of the diameter measurement (3 μm) and the standard deviation of the diameters measured at different angles (1 part in 10^4).

The spatial non-uniformity of the output of the integrating-sphere source is determined by scanning a laser beam within the aperture area. Both lamps were replaced by large-area photodiodes (18 mm × 18 mm).

Table 1. Uncertainty budgets for realizations of the units of luminance and spectral radiance at a wavelength of 600 nm.

Source of uncertainty	100 × Relative standard uncertainty L_v	100 × Relative standard uncertainty L_e (600 nm)
Illuminance/spectral-irradiance standard	0.14	0.25
Integrating-sphere source		
Aperture area (diameter 16 mm)	0.04	0.04
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 photomultiplier tube		0.03
Noise of photomultiplier tube		0.08
Calibration of spectroradiometer		0.11
Temperature dependence of irradiance responsivity		0.05
Non-linearity of photometer	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, 95 % confidence level	0.36	0.62

As the path of the light is reversible, the changes in the signals of the photodiodes should correspond to the spatial non-uniformity in the output of the integrating sphere. The diameter of the measurement beam was 1 mm. The scanning was carried out using laser wavelengths of 488.1 nm, 514.5 nm, and 633.0 nm. The standard deviations of the signals measured for beams completely within the aperture area are 11 parts in 10^4, 10 parts in 10^4 and 7 parts in 10^4, respectively. For the realization of the unit of luminance, a $V(\lambda)$-function-weighted average of the standard deviations was used as the standard uncertainty caused by the non-uniformity of the output of the integrating-sphere source. For the realization of the unit of spectral radiance, the standard deviations were estimated to correspond to typical values in the wavelength regions 360 nm to 500 nm, 500 nm to 570 nm, and 570 nm to 830 nm.

The average luminance on the output of the integrating-sphere source increases linearly by 14 parts in 10^4 per hour. The luminance is measured at the beginning and end of each calibration. An average of the results is used as the reference luminance. The standard uncertainty caused by the instability is calculated from a rectangular probability distribution, corresponding to a measurement time of 1 h.

The uncertainty of the colour temperature of the integrating-sphere source is 25 K. This causes standard uncertainty components of 1 part in 10^4 in the realizations of the units of luminance and spectral radiance, because of the colour-correction factor of the photometer.

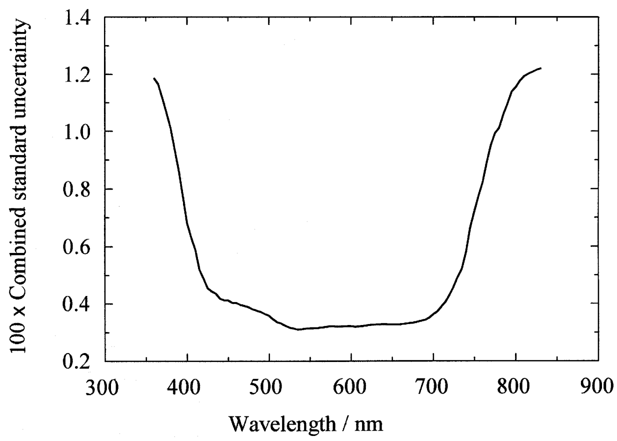

Figure 2. Combined standard uncertainty of the unit of spectral radiance as a function of wavelength.

3.2 Uncertainty components relating to spectroradiometer

The standard uncertainty of the wavelength scale of the spectroradiometer is 0.1 nm. The temperature dependence of the wavelength scale (≤ 0.01 nm/K) is included in the stated uncertainty. The irradiance variation $|dE_e(\lambda)/d\lambda|/E_e(\lambda)$ of the spectrum at a wavelength of 600 nm is 3 parts in 10^3 per nanometre. At shorter and longer wavelengths, the irradiance variations can be as high as 5 parts in 10^2 per nanometre. The uncertainty in the realization of the unit of spectral radiance caused by the wavelength scale of the spectroradiometer is obtained as $\Delta E_e(\lambda) = \Delta\lambda|dE_e(\lambda)/d\lambda|$, where $\Delta\lambda$ is the uncertainty of the wavelength.

The spectrum of the integrating-sphere light source differs from that used in the calibration of the spectroradiometer. The spectral distortion arising from this difference may shift the effective measurement wavelengths compared with the wavelength scale of the spectroradiometer. In the wavelength range 430 nm to 750 nm, the standard uncertainty in the measured spectrum caused by spectral distortion is less than 1 part in 10^4. At shorter and longer wavelengths, the standard uncertainty increases, having a maximum of 9 parts in 10^4 at a wavelength of 760 nm. The effect of spectral scattering in the visible wavelength region is below 1 part in 10^4 when a high-quality double monochromator is used [4].

The dark current of the photomultiplier tube is measured at the beginning of the measurements and subtracted from the measured photocurrents at each wavelength. After subtraction, an average offset of 8.3 pA still appears in the output of the photomultiplier tube. This offset, the reason for which is unknown, is determined by measuring the signal of the spectroradiometer in a completely dark room and then correcting to the measurement results. The stated uncertainty value, obtained as the standard deviation of ten measurements, represents the statistical variation of the offset. In addition to the offset, a short-term noise with a standard deviation of 2.9 pA exists in the output of the photomultiplier tube.

The uncertainty of the calibration of the spectroradiometer includes components arising from the noise and drift of the photomultiplier tube during the calibration of the spectroradiometer. The uncertainty of the standard lamp used in the calibration is included in the uncertainty of the unit of spectral irradiance.

The irradiance responsivity of the photomultiplier tube is very sensitive to the ambient temperature. The change of irradiance responsivity depends on the wavelength, varying from –3 parts in 10^3/K to –7 parts in 10^3/K. At each wavelength, the temperature dependence is linear. A correction has been developed to compensate for the difference between the calibration and measurement temperatures. The temperature dependence of each spectral component is first determined by a linear fit, resulting in a matrix of the slopes and the intercepts. A fourth-degree polynomial as a function of wavelength is then fitted separately to both the slopes and the intercepts, thus yielding a wavelength-dependent correction function. After applying the correction, the maximum error in the measured relative irradiance is reduced to 8 parts in 10^4, which causes a standard uncertainty component of 5 parts in 10^4 in the realization of the unit of spectral radiance.

3.3 Other uncertainty components

The photometer is based on a filtered Hamamatsu S1227 silicon photodiode. The non-linearity of the photodiode is less than 2 parts in 10^4 within the power levels used in the measurements [5], which causes an uncertainty component of 1 part in 10^4 in the realizations of the units of luminance and spectral radiance.

The uncertainty of the alignment of the photometer, the spectroradiometer, and the integrating-sphere source is 0.1°. The standard uncertainty caused by the alignment in the measured luminance is less than 1 part in 10^4. The diffuser in the measuring head of the spectroradiometer further reduces the effect of the alignment in the spectral radiance measurement. The standard uncertainty of the distance measurement is 0.1 mm. The stated value of the standard uncertainty relates to the distance of 800 mm in the luminous intensity measurements.

The effects of diffraction caused by the aperture of the photometer, the baffle, and the aperture of the integrating-sphere source were corrected according to the methods given in [6]. The stated uncertainty value is that remaining after correction.

4. Discussion

A realization of the units of luminance and spectral radiance based on an integrating-sphere light source has been described. The realization is independent of any standard materials, thus avoiding uncertainty related to the ageing of the materials. The combined standard uncertainty of the realization is approximately five times less than that obtainable with methods based on standard materials, but it is greater than that obtainable with methods based on black-body radiators. However, the realization is straightforward and relatively inexpensive compared with methods based on black bodies.

The dynamic range of the luminance calibration is from 250 cd/m^2 to 40 000 cd/m^2. The correlated colour temperature of the source changes slightly when the luminance level is tuned. The spectrum of the source also differs from that of CIE Standard Illuminant A in the wavelength region above 700 nm. The change in colour temperature and the unusual spectrum of the source might cause difficulties if luminance meters with a poor colour-correction factor were calibrated. These effects could be avoided by coupling the lamps to the integrating-sphere source with satellite spheres. This would also allow measurements of lower luminance values, but the upper end of the scale would be significantly lower.

The uncertainty of the unit of spectral radiance is highly dependent on the wavelength. In the wavelength range 410 nm to 730 nm, the standard uncertainty is below 5 parts in 10^3, comparable to that of other methods for realizing the unit of spectral radiance. At shorter and longer wavelengths, the uncertainty increases rapidly. Uncertainty levels could be decreased by improvements in the spectroradiometer. For the long-wavelength region, the lamps could also be changed.

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