Evaluation of calibration methods of a photometer measuring maritime light-emitting diode buoy lanterns

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Abstract. A photometer used for on-line product testing of light-emitting diode (LED) buoy lanterns is calibrated for illuminance responsivity using two different methods. The first method is based on absolute calibration of the photometer with the CIE standard illuminant A light source, combined with spectral correction factors (SCFs) calculated from the measured spectral responsivity of the photometer and relative spectra of the LED lanterns. The second method is based on direct comparison with a characterized reference photometer using the LED lanterns as light sources. Comparison of the resulting correction factors shows that both methods agree within 1%. However, the second method includes geometrical aspects and LED characteristics that caused problems. These problems are discussed and the reasons for recommending the first method are given.
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Subject terms: photometry; light-emitting diodes; metrology.

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1 Introduction

The technology to produce LEDs has improved rapidly and this has quickly brought them wide use in the lighting industry. The robust structure and long lifetime of LEDs make them superior to incandescent lamps in certain applications. The low-light output of a single LED can be compensated by using clusters consisting of dozens up to hundreds of LEDs. With proper lens systems, narrow light paths and therefore relatively high luminous intensity levels are achieved within restricted cones.

Characterization, colorimetry, and photometry of LED light sources are demanding tasks because of sharp spectral features.[1] The spectral responsivities of the photometers used in the characterizations should closely match the $V(\lambda)$ function describing the responsivity of a human eye. Deviations from the actual $V(\lambda)$ curve can produce large errors in the readings when only a narrow portion of the visible spectrum is handled. Spectral correction factors (SCFs) are therefore needed. These factors depend on the spectrum of the light source.

This work focuses on the maritime applications of LEDs. The colors used in navigational lights are white, green, yellow, and red. Traditionally these colors are achieved by using incandescent lamps with colored lenses. Taking into account the long lifetime of LEDs, as well as their low power consumption and low maintenance requirements, the LED lanterns are increasingly used as maritime low-intensity beacons, located on floating devices or on fixed structures at the harbors.

The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) gives recommendations on various navigational aspects, including the photometry of signal lights.[2] The IALA recommends two alternative methods for photometer characterization when measuring LED sources. The first method is more traditional photometry, where SCFs are calculated from the relative spectral responsivity of the photometer and the relative spectra of the lanterns. Final correction factors are obtained by multiplying the SCFs with a correction factor obtained from the CIE standard illuminant A calibration. The second method is quite different, since the LED lanterns are used as standard light sources during calibration, where the photometer is calibrated absolutely against the reference photometer. The relative spectra of the lanterns are also measured, but only to calculate the color correction factors for the reference photometer. In this work, the results that are obtained with these methods are compared and methods themselves are evaluated, leading to discussion and the conclusion that the first method is, despite being laborious, a more practical and applicable way to calibrate a photometer measuring LED sources.

2 Measurements

Helsinki University of Technology (HUT) is the national standards laboratory for optical quantities in Finland. The calibration equipment of HUT includes experimental setups for illuminance responsivity measurements[3] and spectral responsivity measurements.[4] The photometric standard lamp Osram Wi41/G and Sabik LED 155 lanterns (Fig. 1) were used as light sources for illuminance responsivity calibrations.

The device to be calibrated was a photometer head with a 1-in. diffuser (UDT Instruments Model 211) attached to a display unit (UDT Instruments System S370). The photom-

Fig. 1 Sabik LED 155 buoy lantern (height 140 mm, diam 170 mm).

eter head was mounted inside a 600-mm-long black anodized aluminum tube used for stray light protection in online production testing. The photometer head was calibrated and characterized with the tube attached to account for possible systematic effects caused by the tube.

A circular baffle with a diameter of 50 mm was used in front of the photometric lamp. The same baffle was first tested with the lanterns, but it was not found to be suitable for light sources of that kind. The narrow circular baffle in front of the wide LED source introduced a pinhole camera effect on the detector side, producing very nonuniform light distribution. Therefore, a rectangular baffle (height 40 mm, width 115 mm) was used as the stray light shield in front of the lanterns.

Four LED lanterns of different colors were calibrated for the relative spectral irradiance and used as light sources. The lanterns had a ring-shaped polycarbonate lens with a diameter of 160 mm. Equally spaced LEDs (60 in the white and green lanterns, 45 in the yellow and red lanterns) mounted on a circuit board behind the lens produced a relatively uniform radiation pattern in the horizontal plane. The measured horizontal intensity distribution of the red LED lantern is presented in Fig. 2.

2.1 *Illuminant A Calibration*

The photometer was calibrated for illuminance responsivity using the CIE standard illuminant A as a light source at a distance of 4.000 m from the front surface of the photometer diffuser. The reading was compared against the HUT reference photometer, its reference (aperture) plane placed at the same distance.

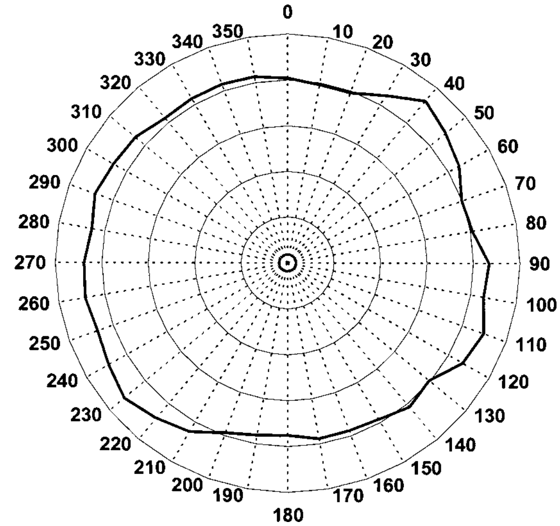


Fig. 2 The horizontal intensity distribution of the red LED lantern.

2.2 *Relative Spectral Responsivity*

The spectral responsivity of the photometer was measured with a reference spectrophotometer at 5-nm intervals.[4] The results were interpolated to 1-nm interval, normalized to relative spectral responsivity $s^*(\lambda)_{\mathrm{rel}}$ as recommended by the CIE[5] and compared to $V(\lambda)$. Results are shown in Fig. 3.

A value describing the quality of the fitting was calculated as

$$f_1' = \int |s^*(\lambda)_{\mathrm{rel}} - V(\lambda)| d\lambda \Big/ \int V(\lambda) d\lambda, \tag{1}$$

where the integrals are calculated over the spectral range 360 to 780 nm. The value obtained from the measurement results was 3.3%, indicating a medium quality photometer (for measuring incandescent, broadband light sources).

2.3 *Spectral Properties of the Lanterns*

The emission spectra of the LED lanterns were measured over the visible region at 1-nm intervals with a calibrated spectroradiometer, traceable to the national standards of spectral irradiance.[6] The measured spectra are presented in Fig. 4.

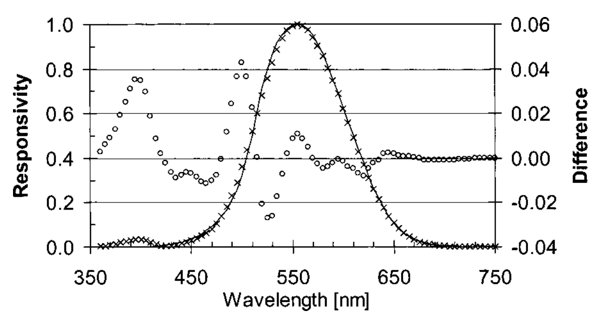


Fig. 3 Comparison of the measured spectral responsivity (crosses, normalized to 1 at 555 nm) with standardized $V(\lambda)$ curve (solid line). Open circles represent the difference between the two curves.

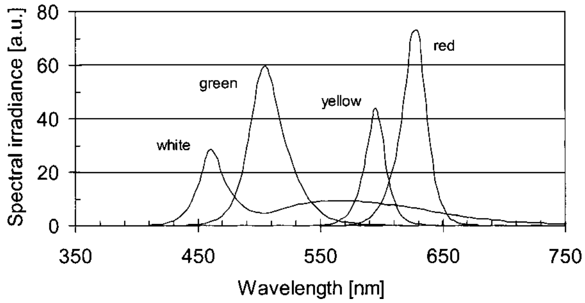


Fig. 4 Measured spectra of the LED lanterns.

Table 1 Correction factors for the photometer. Total correction factor of method 1 includes the correction factor of 0.985 resulting from the illuminance responsivity calibration using the CIE standard illuminant A light source.

	White	Green	Red	Yellow
SCF	1.007	0.974	1.010	1.003
Total correction (method 1)	0.991	0.960	0.995	0.988
Total correction (method 2)	0.989	0.954	1.005	0.984
Difference	0.002	0.006	−0.010	0.004

None of the lanterns had significant spectral components below 412 nm. Therefore, a more appropriate f_1'-value for the device under calibration would be 2.2% as calculated over the spectral range 412 to 780 nm. Within this range the photometer can be considered a high-quality photometer $(1.5\% < f_1' < 3.0\%)$.

2.4 *Direct Calibration with Lanterns*

The spectral responsivity of the reference photometer is known very accurately and it has $f_1' = 1.8\%$. The spectra of the lanterns were used to calculate corresponding color correction factors for the reference photometer. The illuminance values were measured with a distance of 4.000 m between the lens of the LED lantern and the reference planes of the reference photometer, and the photometer under calibration. This calibration procedure was repeated for each of the four lanterns.

3 Comparison of the Obtained Correction Factors

Calibration using the CIE standard illuminant A can be converted to calibration factors for the LED lanterns by using the relative spectral responsivity of the photometer and the measured spectra of the lanterns. Spectral correction factors are calculated[2,7] according to

$$\mathrm{SCF} = \frac{\int S_A(\lambda) s_{\mathrm{rel}}(\lambda) d\lambda}{\int S_A(\lambda) V(\lambda) d\lambda} \frac{\int S_t(\lambda) V(\lambda) d\lambda}{\int S_t(\lambda) s_{\mathrm{rel}}(\lambda) d\lambda}, \tag{2}$$

where $S_A(\lambda)$ is the relative spectrum of the CIE standard illuminant A used for the absolute calibration, $S_t(\lambda)$ is the relative spectrum of the lantern (Fig. 4), and $s_{\mathrm{rel}}(\lambda)$ is the relative spectral responsivity of the photometer (Fig. 3). It should be emphasized that all of the spectral terms in Eq. (2) appear twice, both in the numerator and the denumerator. Therefore, it is not necessary to measure them in absolute terms. When calculating the total correction factors for different LED lanterns using the first method, the obtained SCFs are multiplied by the correction factor obtained from the absolute CIE standard illuminant A calibration.

With the second method, the correction factors for the lanterns were obtained by simply dividing the illuminance measured with the reference photometer by the illuminance measured with the photometer under calibration. The results with the red lantern deviated from the others, and the measurement was repeated with three different rotational angles. Resulting correction factors were 1.003, 1.004, and 1.006. The average of these correction factors for the red lantern was 3.0% higher than the average of the correction factors obtained for the other lanterns. The combined results of the measurements are presented in Table 1.

Deviation in the results with the red lantern was investigated by measuring its vertical spatial intensity with three different lateral angles. The results are presented in Fig. 5, and they confirm that the geometrical and optical axes are not always the same. The position of the peak of the vertical intensity distribution depends on the lateral angle. The largest observed shift of the peak was about 0.5 deg, justifying the slightly larger difference in the compared correction factors.

The expanded uncertainty in the measurements when using the spectral correction factor is 0.7% $(k=2)$. The value includes uncorrelated components of the spectral irradiance and spectral responsivity measurements. Taking into account the expanded uncertainty of standard illuminant A calibration (0.6%), the expanded uncertainty of the total correction factors obtained by the first method is 0.9% $(k=2)$. The expanded uncertainty of the correction factors obtained by the second method is somewhat higher with a value of 1.0% $(k=2)$.

4 Discussion

Accurate photometric calibrations require that the light source be a point source. The LEDs and the lanterns themselves have lenses, with a consequence that the inverse square law does not work accurately, leading to differences as compared to the results acquired by using the standard lamp as a light source.

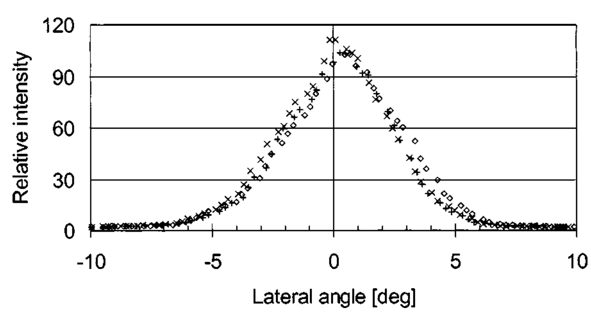


Fig. 5 Spatial illuminance intensity distribution of the red lantern with lateral angles of 0 deg (plus signs), 120 deg (crosses), and 240 deg (circles), as seen in Fig. 2.

The optical axis of an LED source is not necessarily the same as the mechanical axis. Furthermore, the light intensity distribution is not uniform; in fact, it can be very narrow, as was found out when the LED lanterns were studied. Usually the input apertures of the reference photometers used by national standard laboratories are relatively small (diameters of 3 to 10 mm), while the photometers used by industry are equipped with large diffusers (diameters of 13 to 30 mm). Narrow spatial intensity distribution of the light source leads inevitably to the situation where the photometers with different aperture sizes measure different amounts of light. The largest deviation occurs when the photometer apertures are placed at the peak intensity. The effect of different aperture sizes is negligible with calibrations using photometric standard lamps.

Another important aspect relates to the spectra of the LED lanterns. The color coordinates of the navigational light sources must be within certain limits. However, specific color coordinates can be achieved with indefinite amounts of different spectra. LEDs with the same color coordinates, but different manufacturers, most likely do not have the same spectra. To maintain the LED measurement system more easily, it should be invulnerable to situations where the LED manufacturer is changed, or completely new colors are used. Furthermore, all of the LED-based devices (for example, traffic signs) are not suitable to be used as calibration light sources. In those cases, the only possibility is to characterize the measurement photometer properly.

Overall it seems that the first method has several advantages. Absolute level of the reference illuminance is achieved by using a standard lamp (point source) with uniform intensity distribution and a broad emission spectrum. This bypasses the difficulties arising from the geometrical and spatial properties with the LED sources, and provides more stable repeatability. Only one calibration, using CIE standard illuminant A, is needed annually to calibrate the absolute measurement level. If new LED types are used the only additional measurement needed is the measurement of the relative spectrum of the LED to calculate a new SCF. The second method requires full calibration of the photometer with a lantern each time a new LED is used. Thus, the first method requires more work during the first calibration, but further maintenance and upgrading of the measurement system is easier.

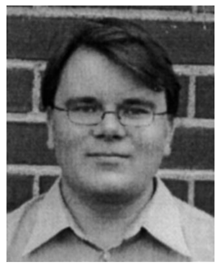
5 Conclusions

Correction factors for the photometer used for measuring maritime LED buoy lanterns are obtained using two alternative methods recommended by IALA. Both methods agree within their uncertainties, which gives high confidence for the measurements. The results indicate that large measurement errors (up to 2.6% for the photometer studied) may occur in LED lantern measurements, even with a high-quality photometer, if spectral deviations of the LED sources from that of CIE standard illuminant A, typically used for photometric calibrations, are not accounted for.

Since both methods give similar results, further evaluation is based on practical matters during and after the calibration. The amount of calibration work required is larger with the first method, but more reliable measurement geometry and easier maintenance afterward make it clearly a choice to be recommended.

References

1. C. C. Miller and Y. Ohno, ‘‘Luminous intensity measurements of light emitting diodes at NIST,’’ *Proc. 2nd CIE Expert Symp. LED Meas.*, pp. 28–32 (2001).
2. *Recommendation on the Photometry of Marine Aids to Navigation Signal Lights*, IALA Recommendation E-122, International Association of Marine Aids to Navigation and Lighthouse Authorities (2001).
3. P. Toivanen, P. Kärhä, F. Manoochehri, and E. Ikonen, ‘‘Realization of the unit of luminous intensity at the HUT,’’ *Metrologia* **37**, 131–140 (2000).
4. F. Manoochehri, P. Kärhä, L. Palva, P. Toivanen, A. Haapalinna, and E. Ikonen, ‘‘Characterisation of optical detectors using high-accuracy instruments,’’ *Anal. Chim. Acta* **380**, 327–337 (1999).
5. *Methods of Characterizing Illuminance Meters and Luminance Meters*, Publication CIE No. 69 (1987).
6. T. Kübarsepp, P. Kärhä, F. Manoochehri, S. Nevas, L. Ylianttila, and E. Ikonen, ‘‘Spectral irradiance measurements of tungsten lamps with filter radiometers in the spectral range 290 nm to 900 nm,’’ *Metrologia* **37**, 305–312 (2000).
7. *Measurement of LEDs*, CIE Technical Report 127 (1997).



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