A Multi-Purpose, Detector-Based Photometric Calibration System for Luminous Intensity, Illuminance and Luminance

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Abstract. A multi-purpose detector based calibration system for luminous intensity, illuminance and luminance has been developed at the Government of the Hong Kong Special Administrative Region, Standards and Calibration Laboratory (SCL). In this paper, the measurement system and methods are described. The measurement models and contributory uncertainties were validated using the Guide to the Expression of Uncertainty in Measurement (GUM) framework and Supplement 1 to the GUM – Propagation of distributions using a Monte Carlo method in accordance with the JCGM 100:2008 and JCGM 101:2008 at the intended precision level.

1. Introduction
In photometry, candela is the base unit of the International System of Units for luminous intensity, which is used to quantify the performance of luminous intensity standard lamps. Illuminance and luminance are the other two fundamental photometric quantities which are commonly used for light assessments of workplaces and characterization of the uniformity of luminous intensity standard lamps respectively. A single detector-based calibration system for the calibration of illuminance meters, luminance meters and luminous intensity of luminous intensity standard lamps has been developed at the SCL. By comparing the developed system with the traditional method using a standard luminous intensity standard lamp as the reference (a source based system), the developed system has the advantage of relatively simple setup for the calibration of luminous intensity standard lamps, illuminance meters and luminance meters.

2. Measurement Setup
The photometric calibrations of luminous intensity and illuminance in the SCL are performed on a long rail system with movable carriages as shown in Fig. 1. The long rail is seated on a rigid surface to minimize the effects due to mechanical vibration. A precision reference photometer head is mounted on a movable carriage which is allowed to move along the railway. The position of the carriage on the rail is monitored by a distance measuring system that provides the absolute position with a resolution of 0.01 mm. The encoder reading is verified by comparison with a laser distance meter, and the expanded measurement uncertainty is determined to be less than 0.2 %.

The reference photometer is thermostatic stabilized to minimize temperature effect. It is calibrated by Physikalisch-Technische Bundesanstalt (PTB) biannually and has an overall uncertainty of 0.9 %. A precision colorimeter is mounted at the end of the rail to monitor the correlated colour temperature of the luminous intensity standard lamp (Osram Wi 41/G or FEL 1000 W) at 2856 ± 50 K. The
uncertainty due to the instability of luminous intensity standard lamp is less than 0.1 %. The standard lamp holder allows 5 axis alignments with very fine adjustment capability to simplify the alignment of the standard lamp. Figure 2 shows the photo of the stage for mounting standard lamp in the SCL. The whole system is accommodated inside a dedicated test chamber, and the light shield enclosure is covered with black velvet. Two to three screens with different aperture sizes are mounted on the rail to reduce stray light effect.

For the calibration of luminance meter, the calibration system is setup on a 3-meter photometric table as shown in Fig 3 and 4. A 12-inch integrating-sphere operated at 2856 ± 50 K is used as a uniform light source. Four tungsten filament lamps with different power ratings are installed in the sphere to cover the luminance range from 10 cd·m⁻² to 4000 cd·m⁻². Two of them are located

Figure 1. Measurement setup in the SCL

Figure 2. Photo of stage for mounting standard lamp
separately in two intermediates 3-inch spheres which are attached to the large sphere. Shutters with adjustable irises are located between the small spheres and the large sphere in order to control the output irradiation level of the sphere-source. A precision aperture is placed on the exit port of the large sphere. The reference photometer located in front of the exit port of the sphere is used on the realization of the luminance unit.

3. Measurement Models
The measurement models of luminous intensity, illuminance and luminance calibration are listed in equation (1), (2) and (3) below respectively.

\[ I_v = \frac{i}{S} (r)^2 \]  
\[ E_{X,c} = \frac{i}{S} \frac{r^2}{(r + x)^2} - E_{X,rad} + C_{stab} \]
where:

$I_v$ is the luminous intensity of the unit under test (UUT),

$i$ is the reading of the reference photometer,

$S$ is the illuminance responsivity of the photometer,

$r$ is the distance between the lamp filament and the front edge of the detector head,

$E_{X,C}$ is the correction for the reading of the UUT (lx),

$x$ is the distance difference between the reference plane defined by the reference photometer head to that of the UUT detector reference plane,

$E_{x,rdg}$ is the UUT reading (lx),

$C_{stab}$ is the correction due to instability of the light source (lx),

$L_v$ is the luminance at the aperture mounted on the exit port of the uniform light source,

$E_v$ is the illuminance at the distance $d$ between the aperture plane of the uniform light source and the photometer head,

$r_1$ and $r_2$ are the radius of the diffuser on the photometer head and the aperture of the uniform light source respectively, and

$A$ is the area of the aperture.

4. Evaluation of Measurement Uncertainties

The uncertainty contributions are due to the reference photometer, distance measurement between luminous intensity standard lamp and reference meter, instability or non-uniformity of the luminous intensity standard lamp, alignment error and stay light error are dealt with in accordance with GUM. According to GUM Supplement 1 (GS1), Monte Carlo method (MCM) is alternative to the GUM uncertainty framework (GUF) when the linearization of the measurement model does not provide an adequate representation or the probability density function of the output quantity departs appreciably from a Gaussian distribution or a scaled and shifted t-distribution. A software tool is developed for implementation of MCM to validate the GUF in accordance with the JCGM 101. It is based on MATLAB, which uses the Mersenne Twister algorithm to generate pseudo-random numbers from a rectangular distribution. The algorithm produces a sequence of 32-bit integers with a long period of $2^{19937} - 1$ and passes a comprehensive test for statistical randomness. A graphical user interface (GUI) is developed to facilitate users to generate an MATLAB-Script file for MCM computation. The coverage interval obtained by the MCM is compared with that obtained by GUF. The graphical display of the MCM result is showed in figure 5. We found that for all cases, the GUF is considered valid for the intended use. The major uncertainty components for luminous intensity, illuminance and luminance are listed in Table 1, 2 and 3 respectively. The best measurement uncertainty for the calibration of luminous intensity standard lamps, illuminance meters and luminance meters are estimated as 1.5% with $k = 2$. 

\[
L_v = \frac{E_v(r_1^2 + r_2^2 + d^2)}{A}
\]
Figure 5. The screen shot of the SCL developed software tool and the graphical display of MCM
Result: Using Approximation in Adaptive Monte Carlo Procedure with $10^{-2}$ Numerical Tolerance for
Stability Test

Table 1 Significant uncertainty components for luminous intensity

| Quantity | Description   | $u(x)$  | Distribution |
|----------|---------------|---------|--------------|
| $i$      | Repeatability | 0.01 %  | $t$          |
| $i$      | Resolution    | 0.05 %  | rectangle    |
| $r$      | Calibration   | 0.21 %  | rectangle    |
| $S$      | Calibration   | 0.45 %  | normal       |
| $S$      | Drift         | 0.46 %  | rectangle    |
|          | Alignment     | 0.2 %   | normal       |

Table 2 Significant uncertainty components for illuminance

| Quantity   | Description   | $u(x)$  | Distribution |
|------------|---------------|---------|--------------|
| $i$        | Repeatability | 0.04 %  | $t$          |
| $i$        | Resolution    | 0.02 %  | rectangle    |
| $S$        | Calibration   | 0.45 %  | normal       |
| $S$        | Drift         | 0.46 %  | rectangle    |
| $E_{x,rdg}$| Repeatability | 0.05 %  | $t$          |
| $E_{x,rdg}$| Resolution    | 0.03 %  | rectangle    |
| $C_{stab}$ | Stability     | 0.06 %  | rectangle    |
| Alignment  |               | 0.36 %  | normal       |
Table 3 Significant uncertainty components for luminance

| Quantity | Description       | $u(x)$ | Distribution |
|----------|-------------------|--------|--------------|
| $i$      | Repeatability     | 0.06 % | $t$          |
| $i$      | Resolution        | 0.03 % | rectangle    |
| $S$      | Calibration       | 0.45 % | normal       |
| $S$      | Drift             | 0.46 % | rectangle    |
| $r_1$    | Calibration       | 0.0009 % | normal |
| $r_2$    | Calibration       | 0.0003 % | normal |
| $d$      | Calibration       | 0.15 % | normal       |
| $A$      | Calibration       | 0.01 % | normal       |
| $A$      | Temperature       | 0.012% | normal       |
|          | Alignment         | 0.058 % | rectangle    |
|          | Stray light       | 0.12 % | rectangle    |
|          | Uniformity of light source | 0.058% | rectangle |

5. Conclusions
The single detector-based calibration system is setup at the SCL. The calibration range for luminous intensity, illuminance and luminance are 35 cd to 3500 cd, 1 lx to 3000 lx and 10 cd·m$^{-2}$ to 4000 cd·m$^{-2}$ respectively. The measurements are carefully evaluated in accordance with the JCGM 100 (GUF) and validated the measurements results with JCGM 101 (MCM). The best measurement uncertainty is estimated as 1.5%. This measurement uncertainty and the wide range of measurements are considered adequate for most measurement applications.

References
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