Colorimetric characterization of LED luminaires

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Abstract. The Optical Metrology Division of Inmetro – National Institute of Metrology, Quality and Technology has recently started the colorimetric characterization of lamps by implementing Correlated Color Temperature (CCT) and Color Rendering Index (CRI) measurements of incandescent lamps, followed by the CFL, and LED lamps and luminaires. Here we present the results for the verification of the color characterization of samples of SSL luminaires for public as well as indoor illumination that are sold in Brazil.

1. Introduction
Over the past few years producers and consumers have become more demanding about lighting quality, requiring lighting products that are not only of good quality but also present alleged protocols for lighting and electrical characteristics, as well as the report of conformity to normative documents issued by qualified experts. There is a clear shift from the incandescent lamps to these more economic models (LED lamps), what is in accordance with last year’s Brazilian government passed legislation on removal from the market of all incandescent bulbs by 2016. That will increase the consumption of LED illumination products.

Here we present the analysis for the verification of the color quality performance of SSL luminaires for public as well as indoor illumination that are sold in the Brazilian market [1].

2. Methods

2.1. The SSL luminaires measurements
In the measurement system used for SSL luminaires, the spectral and angular distributions of LED lamps are measured with a goniophotometer with rotating mirror arm used in association with the spectroradiometer as illustrated in figure 1. Spectral power distribution (SPD) measurements of a reflectance white tile are carried out in the standard 0°:45° illumination observation geometry. This arrangement results in a simple structure of the equipments and reliable measurements in a continuous range of observation angles. The CCT and CRI calculations take into account the measurement geometry and the procedures according to IES LM-79-08 [2].
2.2. Colorimetry measurements of LED luminaires

The ambient conditions, temperature and relative humidity, are maintained at (25 ± 1) °C and (50 ± 5) % respectively. The stabilization of the luminaire system is monitored by following up the uniformity of luminous flux, which occurs when all light emitters (LEDs) are in equilibrium. This occurs in 1 hour approximately. The SSL luminaire is positioned on a goniophotometer LMT-GO DS-2000 at a distance of 16.5 m of the reference tile. An ensemble of walls with adjustable apertures is installed between them to prevent stray light. The distance of the tile to the spectroradiometer is 0.8 m. The measuring directions are the combination of two parameters: the angle $\phi$ representing the position of the luminaire around its vertical axis and the angle $\theta$ representing the angle measured in a vertical plane in manner that $\theta = 0^\circ$ to the downward direction of vertical axis and $\theta = 180^\circ$ to the upward vertical axis. There are two sets of SPD measurements, as determined by the procedure IES LM-79-08: the first is set the angle $\phi$ at 0º and vary the angle $\theta$ at intervals of 10° up to the intensity limit for its acquisition, and the second consists of setting the angle $\phi$ at 90º and varying the angle $\theta$ in intervals of 10° up to the intensity limit as illustrated in figure 2.

2.3. Colorimetric calculations

Both the CCT and the CRI are obtained by measurements of the spectral power distribution of the luminaire performed by the spectroradiometer. The Robertson method is applied to obtain the CCT. We follow Gardner [3] to derive analytical expression for uncertainty in $u$ and $v$ chromaticity
coordinates and an uncertainty in CCT could be achieved. The CRI is calculated according to CIE 13.3 – 1995 – Method of Measuring and Specifying Colour Rendering Properties of Light Sources. The CRI uncertainties are obtained by applying the ISO GUM [4] to derive analytical expressions for the uncertainties following the works of Gardner. In our work, partial derivatives of the calculation equations for color quantities are obtained in analytical form, what is not straightforward, due to the correlations among the chromaticity coordinates. The CCT and CRI calculations for SSL luminaires take into account the measurements geometry and procedures in IES LM-79-08.

3. Results
CCT and CRI were measured for a set of four SSL products, identified as samples J, K, L and M, as presented in table 1. The sample J, K and L are being designed and produced by national manufacturers that performs tests and essays to develop and improve their product. The sample M is sold in the Brazilian market and is produced by an international manufacturer. According to IES LM-79-08, the angle accuracy is not very critical for SSL luminaire measurement. That was experimentally verified using a SSL luminaire named sample M in table 1.

| SSL Luminaires | Quantities | Nominal | 0° Plane measure | 90° Plane measure |
|----------------|------------|---------|------------------|------------------|
| Sample J 72 LEDs 65 W | CCT (K) | 4500 | 4669 | 4665 |
| | U_CCT (K) | 275 | 83 | 83 |
| | Ra | >70 | 77 | 78 |
| | U_Ra | - | 4 | 4 |
| Sample K 90 LEDs 125 W | CCT (K) | 5000 | 4958 | 4903 |
| | U_CCT (K) | 300 | 138 | 83 |
| | Ra | - | 65 | 78 |
| | U_Ra | - | 4 | 4 |
| Sample L 96 LEDs 100 W | CCT (K) | - | 5244 | 5292 |
| | U_CCT (K) | - | 151 | 146 |
| | Ra | - | 73 | 64 |
| | U_Ra | - | 4 | 4 |
| Sample M 49 LEDs 43 W | CCT (K) | 4000 | 4357 | 4305 |
| | U_CCT (K) | - | 74 | 63 |
| | Ra | - | 66 | 65 |
| | U_Ra | - | 4 | 4 |
Polar diagram in figure 3 shows the luminous intensity distribution for the SSL luminaire sample M in the vertical planes corresponding to $\phi = 0^\circ$ (red line) and $\phi = 90^\circ$ (green line). Values outside the frame correspond to the $\theta$.

Figures 4 and 5 show the SPD measured for sample M acquired at intervals of $10^\circ$ from $0^\circ$ to $70^\circ$ for the plane $0^\circ$ and the $0^\circ$ to $60^\circ$ for the plane $90^\circ$, and those were the limiting angles due to intensity dropping. Another set of SPD measurements for the $0^\circ$ and $90^\circ$ plane were performed at steps of $1^\circ$ around the angle where the intensity peaks occur. The maximum deviation for $0^\circ$ plane was found to be around 5 K, and this difference is negligible considering, for example, the calculated 74 K uncertainty value that comes mainly from the colorimetric coordinates at this angle and observation plane.

Figure 3. Polar diagram of luminous intensity distribution for a SSL luminaire sample M

Figure 4. Spectral power distributions of sample M at horizontal angle $\phi = 0^\circ$
For the 90° plane the maximum deviation was found to be around 12 K. At the angle where the more intense peak occurs, the maximum uncertainty from colorimetric coordinates also occurs, and consequently the great value for CCT and CRI uncertainties, and thus we usually do not present the CCT and CRI uncertainties for all the measured angles because they are smaller. Uncertainties are reported in Table 1 for the peak intensity of the measured luminaires. Other studies were carried out in our laboratory in order to examine the influence of the temperature of a typical single LED in the values of the CCT. These studies were carried out employing a thermal controller while measuring different SPD at each temperature. The temperature in the body of a SSL luminaire measured in the laboratory during the measurement is estimated to be around 50 °C using a copper constantan thermocouple probe. A luminaire using LEDs will present an expected shift in correlated color temperature [5] due to higher LED temperature during the luminaire operation, and this explains the differences between nominal and measured CCT. Sample M presents a CCT value around 4300 K, however through calculation and Duv table the CCT nominal category should be ranked 4500 K.

4. Uncertainty Budget
Table 2 shows the uncertainty budget considering a SSL luminaire sample M as an example. It takes into account the components associated with the measurements and the calculations as well. The last component is associated with geometric factors.

| Components                  | Type | Uncertainty(K) |
|-----------------------------|------|----------------|
| Colorimetric coordinates    | A    | 38             |
| Standard lamp certificate   | B    | 2.3            |
| Repeatability              | A    | 0.2            |
| Stability                  | A    | 0.3            |
| Angle variation            | A    | 2.5            |
| Expanded uncertainty (k=2) |      | 74             |

5. Conclusion
In these work we present the measurements methods to provide oversight and guidance on the evaluation of SSL luminaires. This will encourage and accelerate the adoption of high performance
SSL lighting by leading end-user manufacturer collaboration in the areas of performance, evaluation, application, and standardization. Solid-state lighting systems are a viable solution for all those who wish performance, economic and sustainability products. Metrology laboratories are the technology base to support government labeling programs and in a future these programs are important to ensure products of high quality.

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