Review on new developments in Photometry

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Abstract. Focused on light sources like LEDs or combinations of them, the specific needs for their characterization are mentioned and appropriate measurement devices are explained: Photometer bench - 40 m length with camera aided alignment tools and automated holders for sources and photometers - measures in one run luminous intensity and 6 related sensitivity coefficients to state value and associated measurement uncertainty. 2.5 m integrating sphere determines luminous flux values by substitution method with monitored throughput using an LED-cluster - instead of the auxiliary lamp - operated in modulated mode and measured by lock-in technique. Robot-goniophotometer scans the angular intensity distribution designed for a hemispherical mounting and optimized either for industrial needs (fast measurement with 8 heads measuring simultaneously at fixed 2.5 m radius) or for research and calibration capable to move heads on arbitrary traces with variable radius up to 3 m and speeds up to 1 m/s.

1. Introduction

This review on new developments in photometry is focused on LEDs and their combination to arrays or clusters including the needs of industrial measurements, which have to be traced back to national standards and noticed as equivalent to global key comparison reference values. The traditional separation between lamps and luminaires allowed to optimize their different properties individually to get the final combination for a certain illumination application. Simply spoken: lamps were designed for general purpose and characterized by the total luminous flux for a specified correlated color temperature and color rendering index, while luminaries gave the adaptation to the application under constraints like economics of installation and use, and ergonomic (quality of illumination) as well as stylistic factors (design of the luminaire). Besides the general demand for high efficiency, the spectral, angular and aerial distributions are main issues.

Such a separation no longer yields for light sources, which are assembled of a number of LEDs or OLEDs. If these are combined as an extended array for the back illumination of a diffuse transmitting window, the characterization has to use the quantities of luminaires (distance between LEDs is much larger than their maximum size, angular distribution of the LEDs is Lambertian or wider). If the combination forms a compact cluster, then the appropriate characterization has to follow the format known from reflector lamps (minimum distance between the LEDs, narrow or "beamed" angular intensity distribution). The luminous flux of an LED increases (nearly) linear with the forward current, and simultaneously the consumed electrical power increases as well as the temperature. For high power LEDs, with efficiencies comparable to known light sources, the temperature and cooling are main topics, specifically because a rise in temperature will change the luminous flux and will shift the relative spectral power distribution.

2. Photometer bench

The new photometer bench system at PTB is divided in 6 sections up to 17 m length, which allow a maximum distance between source and photometer of 40 m. On one side a 20 kW halogen-lamp operated at CIE illuminant A produces an illuminance up to 10 klx, while on the other side in 30 m distance a 12 kW metal halide lamp produces nearly 100 klx with a spectral power distribution close to daylight. A motor-driven carriage with one spectrometer and up to 6 photometers (reference and test) moves between the two lamps, which varies the two illuminance values by more than two orders of magnitude. The system is intended to characterize e.g. sensors for illumination management, which can be carried out software-controlled including the variation of distance and its measurement by absolute encoding, the change of photometers and sensors, any setting of shutters, amplifiers, and power supplies just as the data acquisition by the DVMs, with the spectrometer and for environmental quantities.

The bench system is also designed for the calibration of modern light sources, which are mounted and aligned (6 degrees of freedom) on two more carriages (similar to the photometer carriage) on a short bench. The short bench is located between the high power lamp and the end of the long photometer bench, with its optical axis rectangular to the axis of the long bench. Two telescopes for the lamp alignment at the ends of the short bench and a third telescope temporarily placed on the long bench are supported by three video cameras, which are connected to a computer. Their images are displayed on a screen and presented to the operator during the manual alignment procedure and finally stored for documentation.

Each carriage for a light source has two more motor-driven axes forming a spherical coordinate system: A vertical axis φ, rectangular to the optical axes of the two benches and a horizontal axis ϑ parallel to the optical axis of the short bench. The luminous intensity value assigned to the light source depends on these settings. The variation of the two rotations ϑ, φ, of the distance d to the photometer, of the dislocation Δx in direction of the short bench and finally of the lamp current J allow the determination of the related sensitivity coefficients for the measured luminous intensity $I = I(\vartheta, \varphi, d, \Delta x, J)$.

The variations are software-controlled as before and they are performed during one run for a typical lamp calibration procedure. This individual knowledge can reduce the measurement uncertainty associated to the luminous intensity value especially for LED-clusters with non-Lambertian angular distributions.

3. Integrating sphere

The determination of the total luminous flux Φ using integrating spheres is well known. Monitoring and correction of any changes of the sphere throughput between the measurements of the reference Φ_{R} and the device under test is explained. Instabilities can be corrected by the division of the measured indirect illuminances E, E_{R} (index "R" refers to reference) with the ratio of the two related photocurrents $y_{\mathrm{AR}}/y_{\mathrm{A}}$ produced by the light of the auxiliary lamp (index "A" refers to auxiliary lamp) and it yields $\Phi = \Phi_{\mathrm{R}}(E/E_{\mathrm{R}})(y_{\mathrm{AR}}/y_{\mathrm{A}})$. Provided the auxiliary lamp is replaced by an LED cluster operated in modulated mode and the related photocurrents are measured using lock-in technique, then the two photocurrents for the ratio can be measured simultaneously with the sequentially determined indirect illuminances. This ratio of photocurrents corrects all changes of the throughput originated by self-absorption, temperature dependence of the coating etc.

In case of high power LEDs or clusters built from these LEDs, cooling with an extended heat sink is needed. Usually the light is emitted to one side of the LED in the related hemisphere, while the other side is connected to the heat sink, which would create very high self absorption, if the whole device would be placed inside the integrating sphere. Therefore, a geometry known as "external source" with the LED located outside the sphere, but close to a sphere port is preferred, and only a partial luminous flux is measured. This quantity is internationally discussed but not yet agreed.

Nevertheless, during industrial production of LEDs all devices are tested and have to be selected in several groups specified for colors and luminous intensity or luminous flux. The measurement of the total luminous flux would take too much time, therefore only a partial luminous flux is measured. The measurement method and the use of reference standards is discussed including effects of stray light and self absorption.

4. Robot-Goniophotometer

Goniophotometers are used for the measurement of the angular luminous intensity distribution of a light source, which is the basis for the fundamental determination of either the total luminous flux or of arbitrary parts of that, known as partial luminous fluxes. The conversion of the Cartesian coordinate system associated to the light source to the related spherical coordinate system $\{r, \vartheta, \varphi\}$ shows that any surface completely enclosing the light source in its center is achieved by only two rotations around the axes $\{\vartheta, \varphi\}$. These axes intersect rectangularly and several mechanical solutions are already known. But there are two disadvantages of these systems, first the long duration (>30 min) for a complete scan in all directions and second the constant radius of the enclosing sphere.

A new robot-goniophotometer of the compact type was developed, which offers several advantages. The fictitious enclosing sphere of the old systems is now divided in two hemispheres, each of which is mechanically realized by rotation of a head around two axes intersecting with an angle of only 45°. The lamp holder with the lamp operated in any burning position is placed in the plane just between the two hemispheres. This concept is already realized in two versions. One robot-goniophotometer is optimized for fast and flexible measurements in industrial environments with a constant radius of about 2.5 m and places for 4 different heads for each hemisphere measuring simultaneously. This allows the combination of a tristimulus head, a spectrometer, an UV-A-radiometer and one more spectral weighting depending on the type of light source.

The robot-goniophotometer realized at the PTB has three robots. One robot aligns the lamp in the center of the instrument and holds it in the defined burning position. The two other robots move the heads on arbitrary traces within that hemisphere with variable radius up to 3 m and maximum speed of 1 m/s in any direction. Within the working volume the mechanical properties (traces, locations) are verified by a laser tracker system taking up to 1000 readings per second for direction and distance with an expanded uncertainty ($k = 2$) of maximum 0.1 mm.

Each head combines tristimulus channels, an UV-A-radiometer and a spectrometer for the visible spectral range. The spectrally integrating channels have individual amplifiers with converters for data acquisition. The installation of the robot goniophotometer is nearly completed and first characteristics will be available at the time of the meeting.

5. Mobile Laboratories

The density of all traffic (automotive, aviation, ship) grows and the daily duration of high density traffic lengthens. This increases the demand for quality in e.g. road illumination, airport taxi-way marking and boat signaling and it reduces the time available for testing the proper functioning of these installations. Therefore, testing facilities denoted as "mobile laboratories", become popular. Often video cameras are mounted around a car, and driven with a speed up to 50 km/h. The recorded sequences are analyzed using digital image processing. Provided a traffic sign produces a specific light-pattern, then the image of the pattern of a standard can be taken as reference and compared relatively with those recorded earlier. If specified values of luminance have to be measured, then the camera system has to be calibrated with a homogeneous standard like the opening of an integrating sphere. These calibration techniques for cameras will be discussed briefly.

6. Conclusion

The facilities explained above are already declared as Major European Investments and by this offered to other National Metrological Institutes for cooperation either in projects for research or as tools for calibration and testing. Comparing the low relative standard uncertainty of the realized units (about 0.2%) with the much higher relative standard uncertainty (> 2%) at the industrial production control, then the reduction of this gap of about one order of magnitude is identified as an important aim, and more effort is spent to support applied photometry and colorimetry with appropriate reference standards and substitution methods.