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Use of Light-Emitting Diodes in Multispectral Systems Design: Variability of Spectral Power Distribution According to Angle and Time of Usage[1]

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Abstract. *Multispectral systems allow the spectral and color characterization of objects using images obtained from several acquisition channels with different spectral sensitivities. Light sources based on light-emitting diodes have started to be used in multispectral systems, mainly to develop low-cost devices for the industry. In this study, the authors examine the variability of spectral power distribution according to the viewing angle of white and single color light-emitting diodes, which can have a significant impact on spectral and color accuracy. This must be taken into account if they are to be used in multispectral systems design. The spectrum drift according to the time of usage of white light-emitting diodes is also analyzed.*
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INTRODUCTION

Multispectral systems have become common in recent years.[1–3] They are used for imaging objects through several acquisition channels with different spectral features, which enables their spectral and color characterization. The number of bands that are required in a multispectral system for an accurate spectral reconstruction may vary depending on the application, but some analyses suggest that less than ten channels are normally needed[4] due to the relatively smooth spectral properties of most surfaces.[5] Multispectral systems are also linked to a high spatial resolution since they normally use a digital camera as a sensor. Therefore, they are capable of providing instant information on a full spectrum of each pixel in the image of the captured scene by means of several mathematical algorithms such as the Moore–Penrose pseudoinverse and the principal component analysis.[1,3,6] Thanks to these features, multispectral systems can be used to develop low-cost devices for industry as they overcome some of the drawbacks of conventional spectroradiometric and spectrophotometric devices, such as their high cost—due to the use of diffraction grating components—and the fact that they only provide a single-spot spectral measurement in a relatively large area. Moreover, multispectral systems highlight certain spectral features of the objects being analyzed, in contrast to conventional imaging systems that only have one or three acquisition channels.

When a multispectral system for measuring color and spectral features needs to be developed, there are two possibilities in terms of the spectral sampling technique. The first configuration, which is the most widespread, features a white light source with a rather uniform spectral power emission and several filters with different spectral transmittances. The second configuration involves multiple colored light sources with different spectral emissions.

Multispectral systems that use the first configuration normally consist of a conventional light source, such as a daylight discharge lamp, a fluorescent or a halogen lamp, and a set of narrowband filters, usually interference filters,[6–9] although liquid crystal tunable filters[1,10] can also be used. The latter are easily controllable via software, although they are expensive. An alternative way of capturing multispectral images with this configuration consists of using a trichromatic RGB digital camera, sometimes combined with supplementary broadband absorption filters.[7,11,12] These systems are simpler and usually cheaper than those described above, since every picture taken with a new filter adds three extra channels. Although this is currently the most conventional configuration for multispectral systems, it is also possible to construct the multiple spectral bands of the system using several light sources with a different spectral emission along the visible spectrum, and therefore a different color. This alternative has considerable potential since the introduction of light-emitting diodes (LEDs)[13] in the market.

An LED is a semiconductor diode that emits light when an electric current is applied to the forward direction of the device. The effect is a form of electroluminescence in which incoherent and narrow-spectrum light (in the order

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of 10 nm of full width at half maximum) is emitted from the p-n junction.[14] The features of the emitted energy depend on the composition and the condition of the semiconducting material and can be infrared (IR), visible, or ultraviolet (UV). There are two ways of achieving white light using LEDs. One is to mix individual LEDs that emit three primary colors (red, green, and blue). The other is to use a phosphor material coating to convert monochromatic light from a blue or UV LED to a broad-spectrum white light. Although the latter LED types are often less efficient, they are simpler to produce and achieve acceptable color rendering for many applications, so most white LEDs in the market are manufactured using this method.

LED illumination technology is inexpensive and efficient, has a long lifecycle, and is constantly evolving. LEDs are widely used as indicator lights on electronic devices and increasingly in higher power applications such as flashlights and area lighting. A few color measuring sensors that use LEDs to light samples can be found in the market, including imaging devices embedded with multiple single color LEDs (such as the Hewlett-Packard and Canon large format printers) and white LEDs in stand-alone spectrophotometer devices (such as Xrite iSis™ and Xrite ColorMunki™).

Other systems use several single color LEDs to create light sources for spectrally matching conventional illuminants.[15,16] In the field of multispectral technology, new systems that use LEDs as light sources for biomedical applications,[17–19] microscopy,[20] and the food and beverage industry[21] have recently been developed. However, most of these devices focus mainly on contrast enhancement and only a few of them are involved in spectral reflectance reconstruction and color measurement of samples.[17,22,23]

LEDs show problems in terms of color consistency and color stability over time.[24,25] Color consistency problems are related to the inherent variation in LED color and lumen output during the production process. To minimize these problems, LED manufacturers measure the chromaticity of each LED and group them into several bins with certain ranges of chromaticity coordinates. This measurement and classification process typically occurs 20–30 ms after the LED is switched on, even if the LED is not yet thermally stabilized.[26] Although color stability is not a fundamental issue for the widespread use of LEDs in the huge consumer market for home, office and industrial goods, it may have a significant impact on metrology applications, such as spectral and color measurements. Therefore, although LEDs are one of the potential light sources for low-cost multispectral systems for industrial applications, a deeper analysis of their properties is required to determine possible limitations and perform the required calibrations to achieve highly accurate spectral and color measurements.

Most LED manufacturers' data sheets include information on performance, such as the relative luminous intensity and chromaticity coordinate change according to forward current and temperature, spectral emissions and directivity patterns (luminous intensity versus angle), and how they change for each bin provided. However, other key characteristics of LEDs for metrological purposes, such as emitted spectrum change according to the viewing angle and spectrum drift with usage[27,28] are not included in the official product data sheets and they are thus analyzed in this study. These features have proven to be fundamental for building systems with high spectral and color accuracy, as described below with a real application using a commercially available spectrophotometric system.

METHOD

Samples

Thirty-four representative LEDs by several commercial companies (BestHongKong, Nichia, Sansen Technology, Philips Lumileds, and Avago) were analyzed. Measurements included the evaluation of ten white LEDs manufactured with a phosphor material coating, since they are the most widely produced and used, and 24 single color LEDs (UV, blue, cyan, green, yellow, amber, red, and pink). We analyzed LEDs with narrow and broad spatial emission, i.e., different directivity patterns from 10° to 140°. Two specimens of each brand model bin were analyzed to study the variability in the results depending on specific samples. All measurements were carried out with the nominal current and voltage values provided by each manufacturer using a stabilized DC power supply (Hewlett Packard 6642A). LEDs were turned on for 5 min to ensure a stable emission before any measurement was taken. Ambient temperature was kept constant at 25 ± 1°C for each LED while taking the measurements to avoid unwanted sources of variability.

Spectral Variability With Angle

We began by characterizing the spectral power distribution of all white and single color LEDs relative to the viewing angle by using an experimental setup that consisted of a Spectro 320 gonio-spectroradiometer by Instrument Systems with an EOP-146 optical probe, which allowed spectral irradiance to be measured inside an area of 33 mm^2 (6.5 mm of diameter) (Figure 1). LEDs were mounted on a motorized rotating system 15 cm away from the former optical probe, thus allowing the LED emission to be measured with a viewing angle of approximately 2.5°. Using this configuration, the spectral emission of the LEDs was characterized at different angles from 0° to 43.2° with incremental angle steps of 1.8°. Differences among angles were analyzed in terms of changes in correlated color temperature (CCT) and CIE 1931-xy chromaticity coordinates.

Spectrum Drift With Time of Usage

It is known that the luminous intensity of LEDs may change with the time of usage, but so may the emitted spectrum. To confirm this effect, we analyzed the spectrum change according to the time of usage of six white LEDs. We used the CDS 2100 spectrophotometer by Labsphere with an integrating sphere, which allowed the spectral characterization of the radiant flux emitted by each of the tested LEDs during 1344 h (56 days). Differences over time were

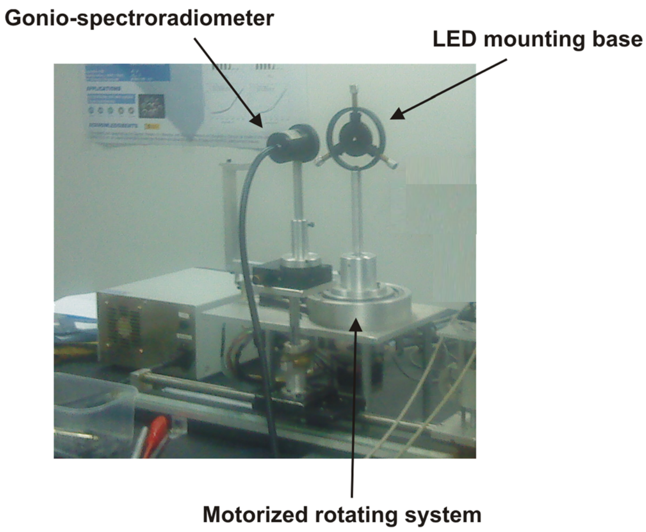

Figure 1. Experimental setup used for the spectral characterization of the LEDs at different angles.

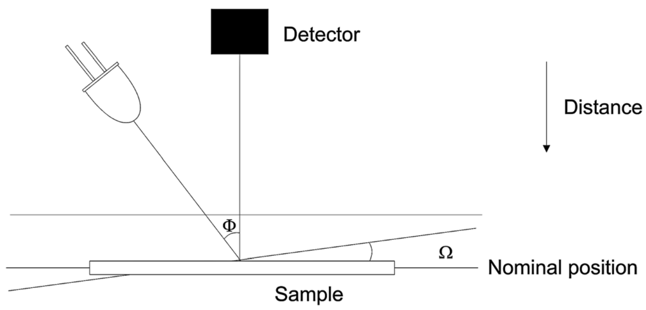

Figure 2. Schematic layout of the spectrophotometric system geometry (illumination angle [$\Phi = 45°$]/measuring angle [$\Omega = 0°$]).

analyzed in terms of changes in CCT and CIE 1931-xy chromaticity coordinates.

Measurements With a Real Spectrophotometric System

In order to reinforce the importance of the emitted spectrum change according to the viewing angle, we analyzed the spectral and color accuracy performance of a commercial spectrophotometric system that used a white LED as a light source and carried out measurements at different angles and distances. Figure 2 illustrates a schematic layout of the spectrophotometric system used with a 45/0 geometry (illumination angle [Φ]/measuring angle [Ω]) at the sample-to-instrument distance recommended by the manufacturer (nominal position). Ideally, spectrophotometers are designed to have an optimum level of spectral and color performance for a specific sample-to-instrument distance. However, there are many applications in which this distance cannot be kept constant. Some examples include a fixed spectrophotometer position at the end of a product manufacturing line and variable sample thickness, and the color control of a printing press in which the spectrophotometer is located at a fixed distance and the paper used is of varying thickness. Another source of variability in the spectral and colorimetric measurements performed with a spectrophotometric system is a slight tilt (Ω) in the tested sample with regard to the instrument.

To analyze these effects, we performed measurements using the spectrophotometric system of the spectral reflectance of a white ceramic tile surface at various rotated positions [angles (Ω) from -2.5° to + 1.5°] and at different distances versus the nominal position (between -1.5 and + 2.5 mm). The results were analyzed according to the CIEDE2000 color differences[29] between each measurement carried out at a specific angle and distance, and the measurement corresponding to the nominal position. The changes in each CIELAB color coordinate, i.e., the L^* (lightness), a^* (red-green component), and b^* (yellow-blue component), were also studied independently.

RESULTS

Spectral Variability With Angle

The spectral irradiances corresponding to a 0° viewing angle of the white and single color LEDs analyzed are shown in Figures 3 and 4, respectively. The main difference between the two specimens of the same LED bin analyzed was the emitted luminous intensity, while the spectrum changes according to the viewing angle and usage was almost the same. Therefore, graphs in this article only show the analysis of one specimen of every LED type. Moreover, since this is a comparative study, only the results from 0° to 10.8° are given for the analysis of the spectrum, which changes according to the viewing angle due to the fact that larger angles provided measurements with a high level of noise in the case of LEDs with narrow directivity patterns.

Figure 5 shows the spectral irradiance at different viewing angles of a specific white LED with 15° of directivity (Brand3 White 15°). It can be seen that the overall irradiance decreases with the viewing angle, as expected. However, if the normalized spectra are studied instead, it can also be observed that while the bluish part of the spectrum maintains a constant shape, the yellow area has a different emission contribution depending on the viewing angle. Meanwhile, the higher the viewing angle, the lower the luminous intensity of the emitted light of the white LED and the more yellowish it is. Figure 6 shows the spectral irradiance at different viewing angles of a white LED with a broader directivity pattern (Brand2 White 140°). In this case, the overall irradiance decreases with the angle at a much lower ratio than the former LED with 15° of directivity. Furthermore, the normalized spectra reveal that both the bluish and the yellowish parts of the spectrum maintain a more constant shape until a 10.8° rotation angle is reached. The other white LEDs were analyzed in the same way and the results varied slightly depending on the manufacturer and the directivity pattern but they all showed similar trends: the broader the directivity pattern of the LED, the lower the emitted luminous intensity, but both the "yellowish" effect and the luminous intensity change according to the viewing angle are also lower. Figure 7 shows the yellowish effect according to the viewing angle dependence of the white LEDs

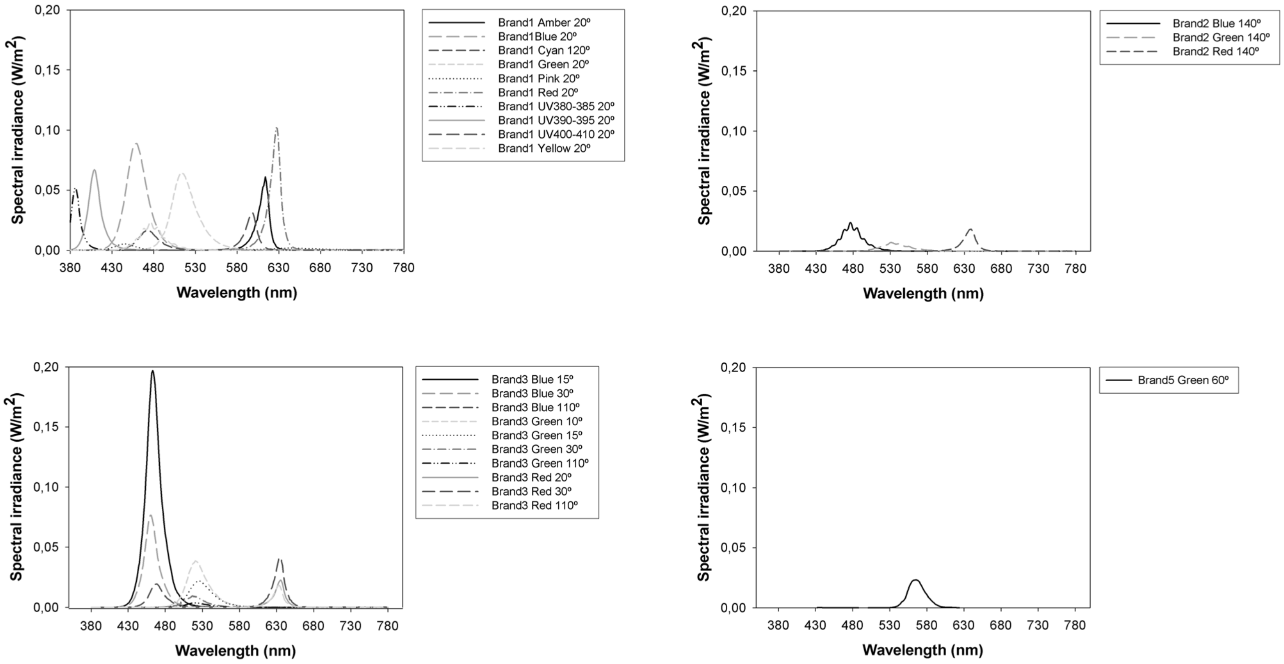

Figure 3. White LEDs spectral irradiance (W/m^2) at a 0° viewing angle.

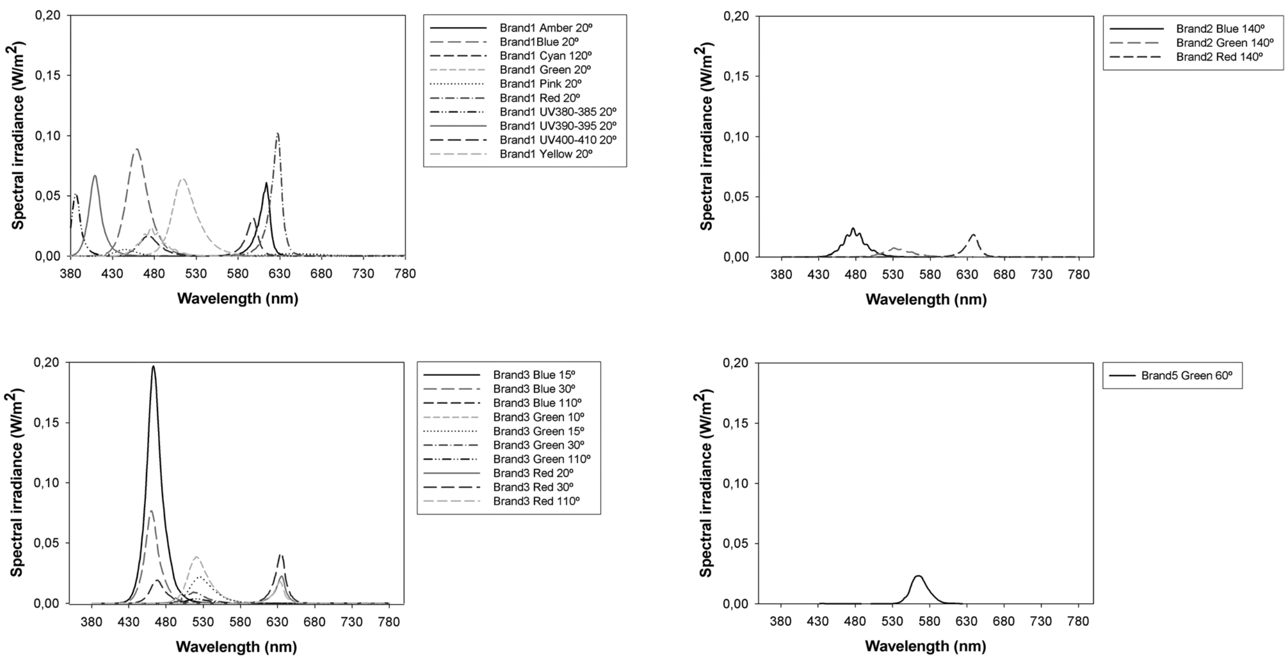

Figure 4. Single color LEDs spectral irradiance (W/m^2) at a 0° viewing angle.

that were analyzed. In this figure, the CIE 1931-xy chromaticity coordinates corresponding to each viewing angle for each LED are presented in a chromaticity diagram. Again, it can be observed that overall narrower directivities (70° or less) are linked to a larger yellowish effect, i.e., to a larger variation of the chromaticity coordinates. This behavior led to a noticeable decrease in the CCT of the white LEDs according to the viewing angle (Figure 8). Table I reports the mean CCT differences between the 0° direction and the other viewing angles, as well as the changes in the CIE 1931–xy chromaticity coordinates. Results are given for all analyzed LEDs as well as for LEDs with high and low directivity patterns. The values found show that differences among angles are generally much higher in the case of white LEDs with narrower directivities.

Besides the white LEDs, different single color LEDs across the full visible spectrum were analyzed to assess the spectral irradiance change according to the viewing angle. Most single color LEDs maintained a constant spectrum independent of the viewing angle, with changes in the chromaticity coordinates (CIE-1931 standard observer) similar to or lower than 0.001 (x and y). As an example, Figure 9 shows the normalized spectral irradiance at different viewing angles

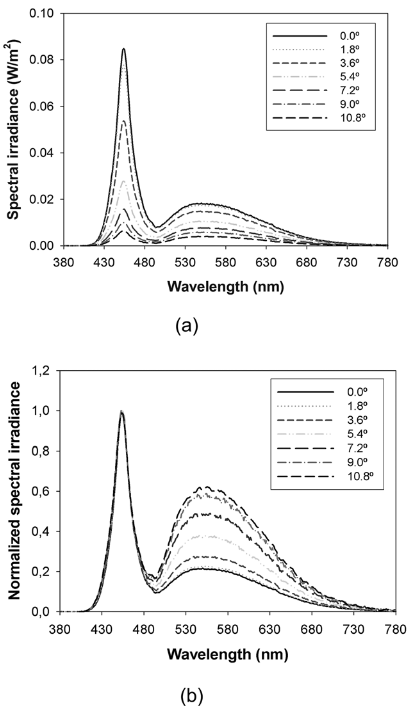

Figure 5. (a) Brand3 White 15° spectral irradiance (W/m^2) at different viewing angles and (b) normalized spectral irradiance.

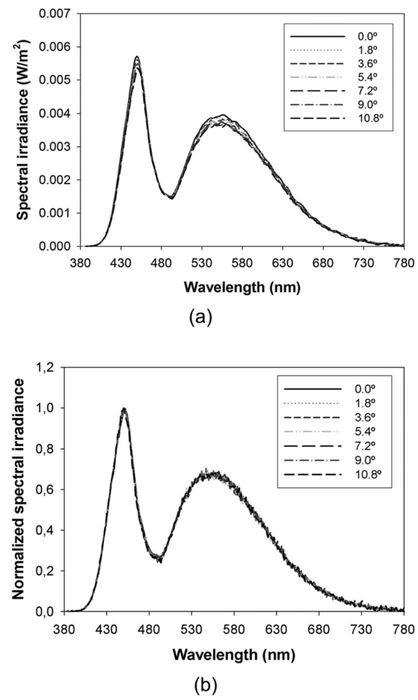

Figure 6. (a) Brand2 White 140° spectral irradiance (W/m^2) at different viewing angles and (b) normalized spectral irradiance.

of three representative LEDs with the same directivity pattern (Brand1 Red LED 20°, Brand2 Green 20°, and Brand3 Blue 20°). We found only two single color LEDs that did not follow this behavior, as illustrated in Figure 10. For these LEDs, changes in the chromaticity coordinates of $x = 0.006$ and $y = 0.000$ (Brand1 Red 20°) and of $x = 0.012$ and $y = 0.007$ (Brand1 Amber 20°) were measured between the angles of 0° and 10.8°. However, it can be concluded that the spectral changes of most of the single color LEDs according to the viewing angle were negligible compared with those obtained in white LEDs with a similar directivity pattern.

Spectrum Drift With Time of Usage

Figure 11 shows the spectrum drift over time of six white LEDs analyzed in terms of correlated color temperature. Table II reports the mean difference in CCT between the first measurement (0 h) and the other measurements performed over time, and the changes in the CIE 1931–xy chromaticity coordinates. Variations found in this case are much lower than those obtained according to the viewing angle for LEDs with narrow directivity patterns, in which CCT was found to decrease. Color changes over time are comparable with the variations observed in LEDs with broader directivity patterns. Therefore, although there is a slight variability in the spectral emission and color over time, this effect is negligible.

Measurements With a Real Spectrophotometric System

Finally, to assess the importance of the spectral power distribution changes according to the viewing angle, we analyzed the spectral and color accuracy of a commercially available spectrophotometric system using a white LED as a light source. Using the schematic layout formerly shown in Fig. 2 with a 45/0 geometry, the spectrophotometric system was used to measure a white ceramic tile surface at different angles and distances. The results provided CIEDE2000 color differences with respect to the measurement at the nominal position, i.e., that recommended by the manufacturer, as shown in Figure 12. The CIEDE2000 analysis shows that the color accuracy degradation is almost symmetrical to the angle and gets worse the further, it is from the ideal (nominal) position. Similar behavior is observed when the changes in the lightness coordinate (L*) are analyzed independently. As expected, measurements performed at rotated positions and at distances closer to or further away from the nominal position provide spectral results that are above or below the result obtained at the nominal position, since the overall amount of light reaching the white ceramic tile changes.

On the other hand, the variability of the a* coordinate (a*) according to the rotation angle and distance is very low. However, while changes according to the angle of the b* coordinate (b*) are also small, relevant symmetrical changes in distance are observed, regardless of whether the sample gets closer to the nominal position or further away from it. One must have in mind that when a 45/0 spectrophotometer architecture is used, a change in the sample-to-instrument distance also involves a change in the illumination angle (Φ), particularly when a point light source is used (see Fig. 2). Thus, if the emitted spectrum of the white LED changes according to the viewing angle, as found in this study, the spectral profile of the light reaching the white ceramic tile surface at a certain distance is different

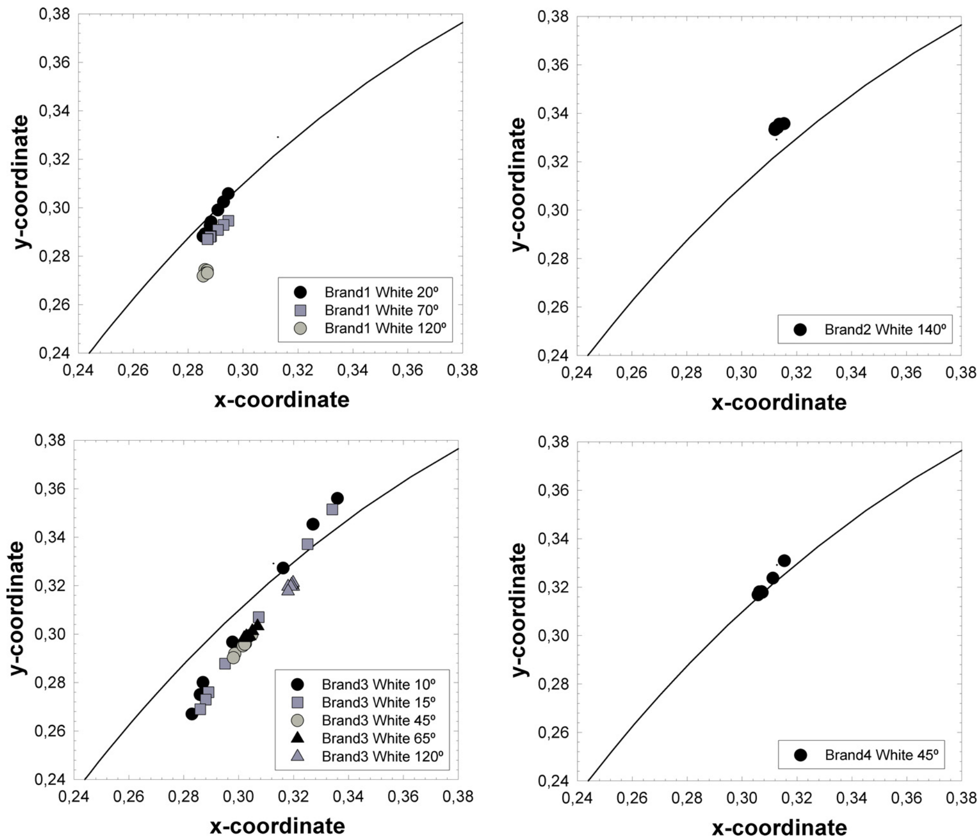

Figure 7. CIE 1931-xy chromaticity coordinates at different viewing angles for the white LEDs. The spectral locus is also shown in the chromaticity diagram.

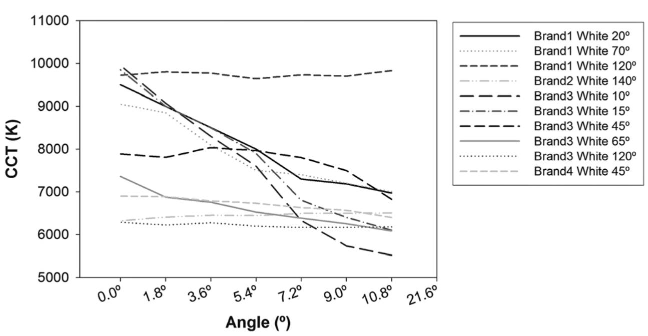

Figure 8. CCT of the white LEDs at different viewing angles.

from that at the nominal position, and, therefore, the color accuracy of the spectrophotometric system degrades with distance. If b* changes and a* remains almost the same, this means that the yellowish effect is the root cause of the color measurement variability found between different distances. This behavior is in line with the previous results obtained from the analysis of independent white LEDs.

Taking into account, that the white LED is positioned approximately 7 mm from the sample in the spectrophotometric system, we can demonstrate that distances differing more than 1 mm from the nominal position are equivalent to changes in the illumination angle (Φ) of 6.8° or more. If there is a 2.5 mm difference, the change in the illumination angle is around 13.6°. This explains why the variability observed at

Table I Differences in correlated color temperature (CCT) and CIE 1931-xy chromaticity coordinates (x,y) between 0° and the other angles (#°) of the white LEDs. The mean absolute differences corresponding to all white LEDs and LEDs with narrow ($\leq$70°) and broad ($>$70°) directivity patterns are given.

$\Delta CCT = \lvert CCT(\# \text{ deg}) - CCT(0) \text{ deg}\rvert$			
Angle (deg)	All directivities	Directivity $\leq 70°$	Directivity $> 70°$
0.0	0	0	0
1.8	346	431	54
3.6	602	832	65
5.4	873	1205	99
7.2	1217	1695	102
9.0	1398	1952	105
10.8	1601	2229	136
$x = \lvert x(\# \text{ deg}) - x(0) \text{ deg}\rvert$, $y = \lvert y(\# \text{ deg}) - y(0) \text{ deg}\rvert$			
Angle (deg)	All directivities	Directivity $\leq 70°$	Directivity $> 70°$
0.0	0.000, 0.000	0.000, 0.000	0.000, 0.000
1.8	0.001, 0.002	0.001, 0.002	0.001, 0.002
3.6	0.003, 0.005	0.004, 0.006	0.001, 0.002
5.4	0.007, 0.012	0.010, 0.016	0.001, 0.002
7.2	0.011, 0.019	0.015, 0.026	0.001, 0.002
9.0	0.014, 0.024	0.020, 0.034	0.001, 0.003
10.8	0.016, 0.026	0.022, 0.036	0.002, 0.003

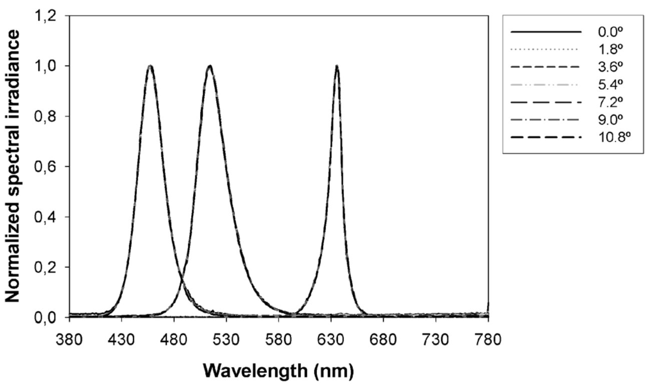

Figure 9. Normalized spectral irradiance of three single color LEDs (Brand1 Red LED 20°, Brand2 Green 20°, and Brand3 Blue 20°) at different viewing angles.

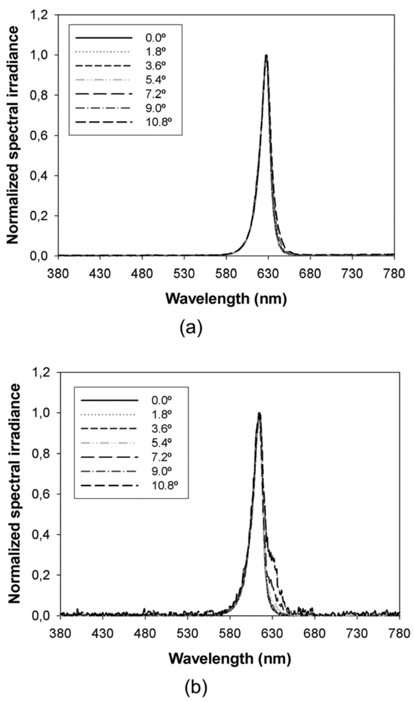

Figure 10. Normalized spectral irradiance of single color LEDs at different viewing angles: (a) Brand1 Red 20°, (b) Brand1 Amber 20°.

the rotated positions [between angles (Ω) of −2.5 and 1.5°] is lower than that observed with changes in distance.

CONCLUSIONS

White LEDs designed with a blue-emitting LED coated with a yellow-emitting phosphor emit light, whose spectrum changes according to the viewing angle, probably due to the nature of the technology used by manufacturers to coat them. Analyses demonstrated that the narrower the directivity of LEDs, the higher the yellowish effect, and that CCT decreases with the viewing angle. Therefore, if the luminous intensity is sufficient for the application, white LEDs with a broader directivity pattern show a more stable spectral power distribution at broader viewing angles. Therefore, it is recommended that they be used in multispectral systems design rather than white LEDs with narrow directivity patterns. Moreover, most single color LEDs tested did not show a spectrum change according to the viewing angle compared with white LEDs with similar directivity patterns. Therefore, they are also highly recommended as light sources in multispectral systems. However, as we have demonstrated, it is always possible to find a single color LED with a slightly different behavior. Therefore, as in the case of white LEDs, each single color LED should be analyzed before it is used for any metrological purpose.

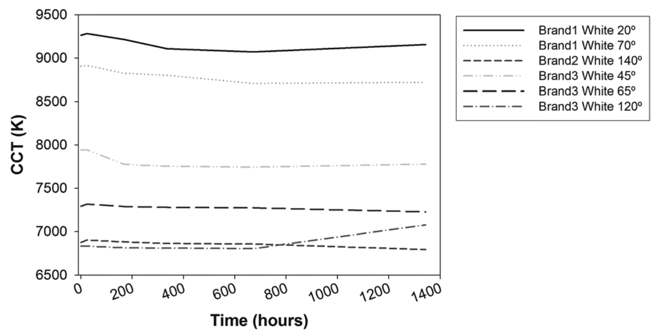

Figure 11. CCT of white LEDs with time of usage.

Table II Differences in correlated color temperature (CCT) and CIE 1931-xy chromaticity coordinates (x and y) over time. The mean absolute differences between 0 h and other times (#h) are given for the six white LEDs analyzed.

Time (hours)	$\Delta CCT = \lvert CCT(\#h) - CCT(0h)\rvert$
0	0
24	15
168	55
336	83
672	110
1344	141
Time (hours)	$x = \lvert x(\#h) - x(0h)\rvert$, $y = \lvert y(\#h) - y(0h)\rvert$
0	0.000, 0.000
24	0.000, 0.000
168	0.001, 0.001
336	0.001, 0.001
672	0.001, 0.001
1344	0.002, 0.002

The spectrum drift with respect to the time of usage of white LEDs was also analyzed. The variation found in this case is small compared with that obtained at different viewing angles for white LEDs with narrow directivity patterns and comparable to that found for white LEDs with a broader spatial emission.

Finally, it has also been proven that noticeable color differences can be found with standard spectrophotometric systems that use white LEDs as light sources due to changes in their spectral emission at different viewing angles.

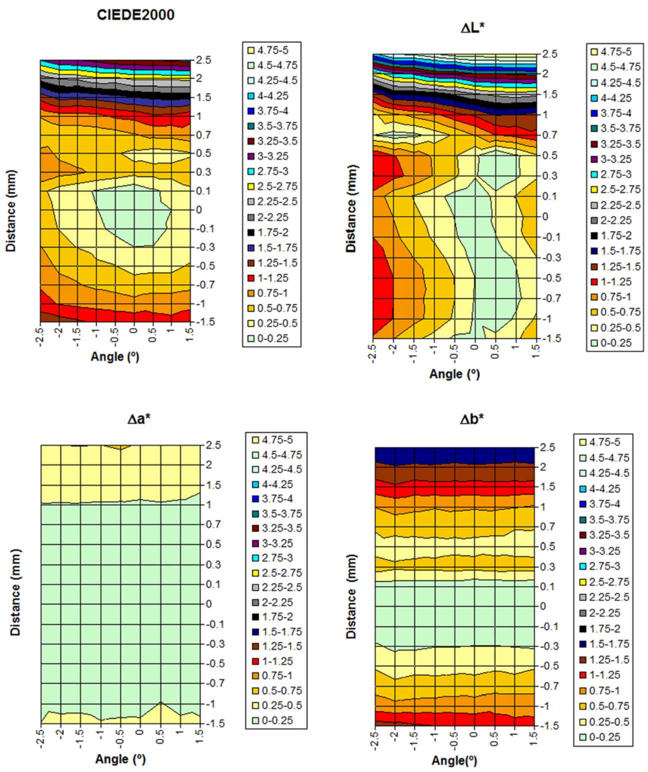

Figure 12. CIEDE2000 color differences between the measurements performed on a white ceramic tile surface at different angles and distances with respect to the nominal position. (a) CIEDE2000 color difference. (b) Same analysis expressed only in L* terms. (c) In a* terms and (d) in b* terms.

Therefore, the illumination system always needs to be calibrated with a known reference at different angles and distances.

The analysis performed in this study also reveals that it is currently very difficult to find white LEDs in the market with sufficient power below 400 nm. Therefore, single color LEDs are recommended to completely cover the visible spectrum in multispectral systems.

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