# Spectral Variability of Light-Emitting Diodes with Angle

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## Abstract

*Multispectral systems allow the spectral characterization of the scene through several acquisition channels with different spectral features. The spectral sampling can be done by using transmittance filters and a white light source or illuminating the scene using light sources with different spectral emission characteristics. Light-emitting diodes based light sources have started to be used in multispectral systems, mainly to develop low-cost devices for the industry. In this study we analyze the spectral power distribution and color variability of white and single color light-emitting diodes relative to the viewing angle, and highlight some aspects that must be taken into account if these light sources want to be used in a multispectral system.*

## Introduction

The use of multispectral systems has become more generalized in the last years.[1-3] These systems allow the spectral characterization of the scene through several acquisition channels with different spectral features. The number of bands involved in a multispectral system for an accurate spectral reconstruction may vary depending on the application but according to some analyses, less than 10 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.[3,6] Thanks to all these features, multispectral systems can be used for developing low-cost devices for the industry since they allow overcoming some of the drawbacks that conventional spectroradiometric and spectrophotometric devices have, such as their high price due to the use of diffracting grating components, and the fact that they only provide a single spot spectral measurement with a relative large area. Moreover, the use of multispectral systems allows some features of the objects being analyzed to be highlighted rather than in conventional imaging systems with only one or three acquisition channels.

When a multispectral system for measuring color and spectral features needs to be developed, two possibilities can be used regarding the spectral sampling technique. On one hand, the most commonly used configuration is made of a white light source with a rather uniform spectral power emission together with several filters with different spectral transmittances. On the other hand, multiple colored light sources with different spectral emission can also be used.

Multispectral systems that use the first configuration normally consist of a conventional light source, such as a daylight discharge lamp or a halogen lamp, and a set of narrowband filters, commonly interference filters.[6,7] Besides interference filters, liquid crystal tunable filters can also be used,[1] which 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 combined with broadband absorption filters.[6-9] These systems are simpler and usually of lower cost than those described previously, since every picture taken with a new filter adds three channels.

Although this is the more conventional configuration for multispectral systems, another approach is also possible: to construct the multiple spectral bands of the system using several light sources with different spectral emission along the visible spectrum, and therefore different color.[10,11] This alternative has a high potential since the irruption of light-emitting diodes (LEDs)[12] in the market.

An LED is a semiconductor diode that emits light when an electrical current is applied in the forward direction of the device. The effect is a form of electroluminescence where incoherent and narrow-spectrum light (in the order of ten nanometers wide) is emitted from the p-n junction.[13] The color of the emitted light depends on the composition and condition of the semiconducting material, and can be infrared (IR), visible (VIS), and ultraviolet (UV). On the other hand, white light can be achieved with LEDs in two main ways.[14] 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 broad-spectrum white light. Although these last types of LEDS have a lower efficiency than normal LEDs, they are simpler to produce and use (individual colored LEDs respond differently to drive current, operating temperature, dimming, and operating time) and get good enough color rendering. Then, the majority of white LEDs now on the market are manufactured with this method.

LED illumination technology is very cheap, efficient, with high life expectancy, and 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 sensors that use LEDs to light samples can be found in the market, such as multiple single color embedded in imaging devices (like in *Hewlett Packard* or *Canon* printers) and white LEDs in stand-alone color measurement spectrophotometric devices (such as *Xrite iSis* and *Xrite ColorMunki*).

However, LEDs have problems with color consistency and stability over time.[15,16] Color consistency is a problem because of the inherent variation in LED die color and lumen output during the production process and change with time and temperature. To minimize this problem, LED manufacturers measure the chromaticity of each LED and group them into several bins. A bin refers to a certain range of chromaticity coordinates for different applied intensities. On the other hand, color stability is not a fundamental issue for its wide use in the huge consumer market for home, office or industrial goods manufacturing applications. However, it may have a great impact in metrology applications, such as spectral and color measurements. Therefore, although LEDs are one of the potential light sources to develop low-cost multispectral systems for the industry, a deep analysis of LEDs color illumination properties must be done to know their possible limitations and perform the required calibrations beforehand to get high accurate spectral and color measurements.

Most LED manufacturers' product datasheets include different information about its performance, such as ICI chromaticity and luminous intensity diagrams for each bin, forward current vs. relative luminous intensity, ambient temperature vs. forward current, ambient temperature vs. relative luminous intensity, forward current vs. chromaticity coordinates, relative spectrum, ambient temperature vs. chromaticity coordinates, and luminous intensity vs. angle. However, other key performance parameters to use LEDs for metrological purposes have not been found in any product official datasheet. A change of the spectral emission of the LED with the viewing angle is one of the most important issues, since it can produce a different spectrum of light at every location of the imaged scene of a multispectral system. This can highly degrade the spectral reflectance reconstruction of samples and therefore, the spectral and color accuracy performance of the multispectral system. For this reason, in this study we analyze the spectral power distribution and color variability of white and single color LEDs illumination patterns relative to the viewing angle, and highlight some aspects that must be taken into account if these light sources want to be used in a multispectral system.

## Method

We carried out the characterization of the spectral power distribution of the LEDs relative to the viewing angle, using an experimental setup which consisted of a gonio-spectroradiometer. The spectroradiometer used was the Instrument Systems model Spectro 320 with the optical probe EOP-146, which allowed the measurement of spectral irradiance inside an area of 33 $mm^2$ (6.5 mm of diameter). LEDs were mounted on a motorized rotating system 15 cm far away from the former optical probe, thus allowing the measurement of the LED emission with a viewing angle of 2.5º (degrees) approximately.

Using this configuration, the spectral emission of several LEDs available in the market was characterized at different viewing angles, specifically from 0º to 43.2º. The angle incremental steps were of 1.8º until 10.8º to have the highest possible resolution at low angle rotations and of 10.8º from then on until 43.2º. Measurements were carried out with the nominal voltage and current values provided by each LED manufacturer. Five minutes were used to warm up the LEDs and assure a stable emission in all cases. Ambient temperature was kept constant while taking the measurements for each LED to avoid unwanted sources of variability.

A broad sample of representative LEDs of several commercial companies were analyzed using this setup: BestHongKong, Nichia, Sansen Technology, and Philips Lumileds. For each company, measurements included the evaluation of both white LEDs built with a phosphor material coating and single color LEDs (UV, Blue, Cyan, Green, Yellow, Amber, Red, Pink). Different directivity patterns (10º to 140º), i.e. different spatial emissions, of each LED were analyzed, although for LEDs with very narrow directivity patterns (10º or 15º) measurements with more than 10º of rotation angle may show a lot of noise due to the very low power received by the detector. Two specimens of each brand model bin were analyzed to study the variability in the results depending on specific samples.

Finally, once the LEDs had been evaluated independently and in order to assess the importance of the emitted spectrum change with the angle, we analyzed the color accuracy performance in terms of CIEDE2000 color differences of a commercial spectrophotometric system using a white LED as a light source at different angles and distances. Figure 1 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 where this distance cannot be exactly kept constant. Another source of variability in the spectral and colorimetric measurements performed with a spectrophotometric system can be a slight tilt (Ω) in the tested sample with respect to the instrument. To analyze these effects, in this study we performed measurements with the spectrophotometric system of the spectral reflectance of a white ceramic tile surface at different rotated positions (between angles (Ω) of -2.5 and +1.5º) and at different distances versus the nominal position (between -1.5 and +2.5 mm). The obtained results were analyzed in terms of CIEDE2000 color differences between each measurement carried out at a specific angle and distance, and that corresponding to the nominal position. The changes in terms of each CIELAB color coordinate, that is, the L* (lightness), a* (red-green component), and b* (yellow-blue component) were also studied independently.

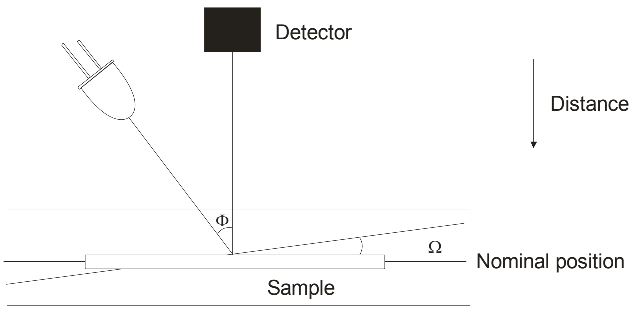



***Figure 1**. Schematic layout of the spectrophotometric system geometry [illumination angle (Φ = 45º) / measuring angle (Ω = 0º)].*

## Results

The spectral irradiances corresponding to a 0º viewing angle of all the white and single color LEDs analyzed are shown in figures 2 and 3, respectively. Since the main difference among specimens of the same LED bin was the emitted luminous intensity while their emitted spectrum change with the viewing angle was very similar, graphs of this study only show the analysis of one of every LED type. This implies that a closed loop controlled electric circuit should be designed to assure the right current is applied to the LED so the emitted intensity is the desired one and constant.

Figure 4 shows the spectral irradiance at different viewing angles of a specific white LED with a directivity pattern of 20º. It can be seen that the overall radiant power decreases with the angle (as expected). However, if the normalized spectra is studied instead (Figure 5), it can also be observed that while the bluish part of the spectrum maintains a constant shape, the yellow region has a different contribution depending on the viewing angle. Then, the higher the viewing angle, the lower the intensity of the emitted light and more yellowish it is.

All the other white LEDs were analyzed in the same way. Results vary depending on the manufacturer and the directivity pattern but all show similar trends: the broader the directivity pattern, the lower the emitted luminous intensity, but both the ‘yellowish’ effect and the intensity change with the viewing angle are also lower. This can be seen at figure 6 where the spectral irradiance at different viewing angles of a specific white LED with 140º of directivity is shown. It can be seen that the overall radiant power decreases with the viewing angle at a much lower intensity than the white LED with 20º of directivity. Furthermore, if the normalized spectra is studied (Figure 7), it can also be seen that both the bluish and yellowish parts of the spectrum maintain a more constant shape until 10.8º rotation angle.

As a summary, figure 8 shows this ‘yellowish’ effect with angle dependency of all white LEDs analyzed. To construct this graph, the maximum irradiance in the bluish part of the spectrum has been divided by the maximum at the yellowish part for each viewing angle. Then the data has been normalized so the ratio is “1” at the starting point (0º). This allows illustrating all white LEDs performances in a single graph. It can be observed that narrower directivity patterns are in general linked to a larger ‘yellowish’ effect.

Table 1 reports the mean differences in terms of the CIE 1931–xy chromaticity coordinates between the 0º direction and the rest of viewing angles. Results are given for all analyzed white LEDs as well as for LEDs with high and low directivity patterns. The values found show again that differences among angles are in general much higher in the case of white LEDs with narrower directivities.

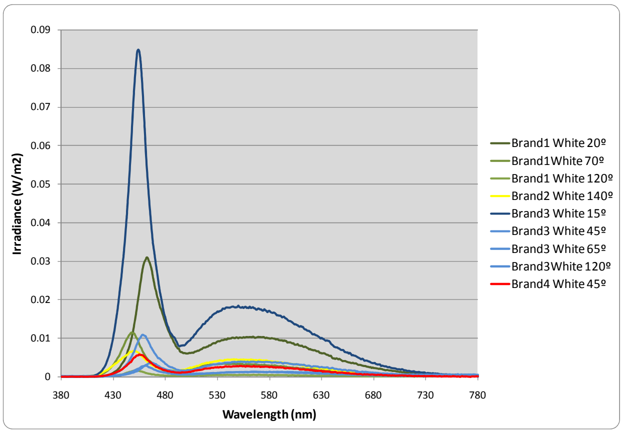



***Figure 2**. White LEDs spectral irradiance (W/m$^2$).*

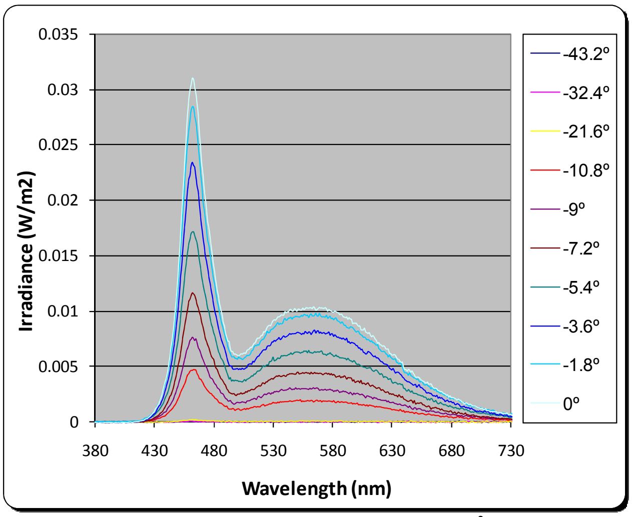



***Figure 4**. Brand1 white LED 20º spectral irradiance (W/m$^2$) at different viewing angles.*

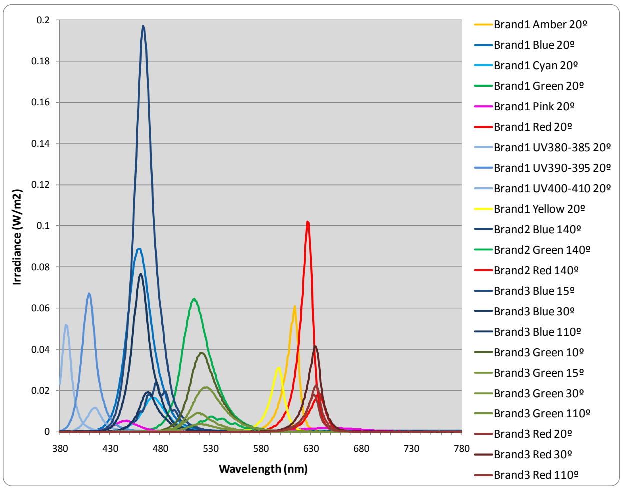



***Figure 3**. Single color LEDs spectral irradiance (W/m$^2$).*

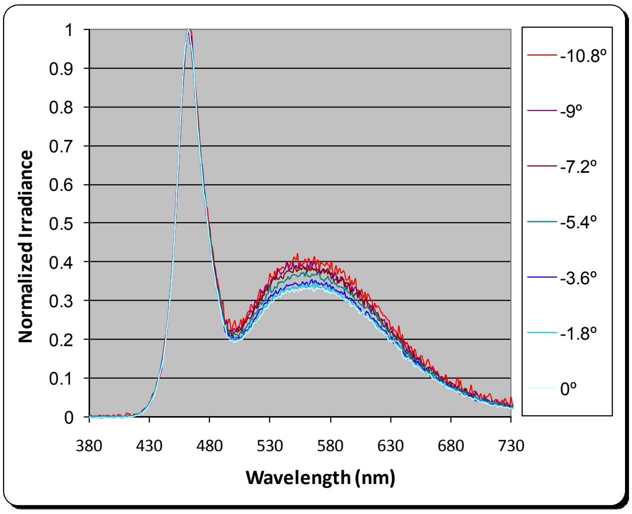



*Figure **5**. Brand1 white LED 20º normalized spectral irradiance (W/m$^2$) at different viewing angles. Data of angles higher than 10.8º have been omitted due to the high noise.*

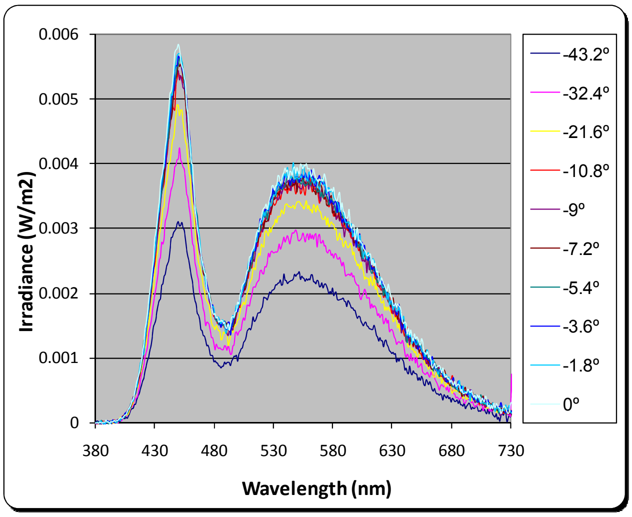



*Figure 6. Brand2 white LED 140º spectral irradiance (W/m2) at different viewing angles.*

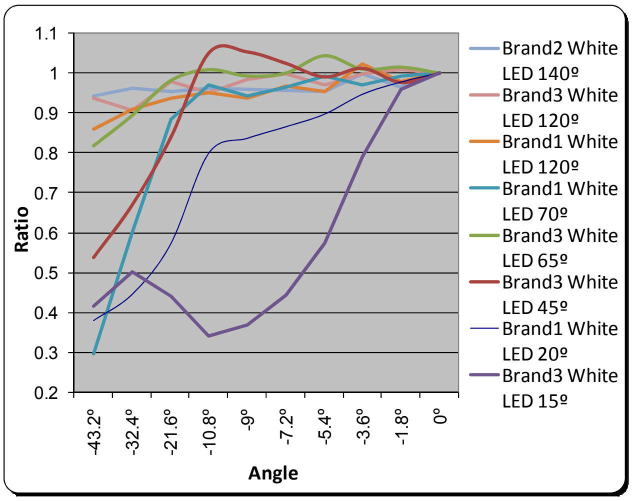



***Figure 8.** Ratio of the white LEDs maximum irradiance peak in the bluish part of the spectrum divided by the maximum at the yellowish part at different viewing angles.*

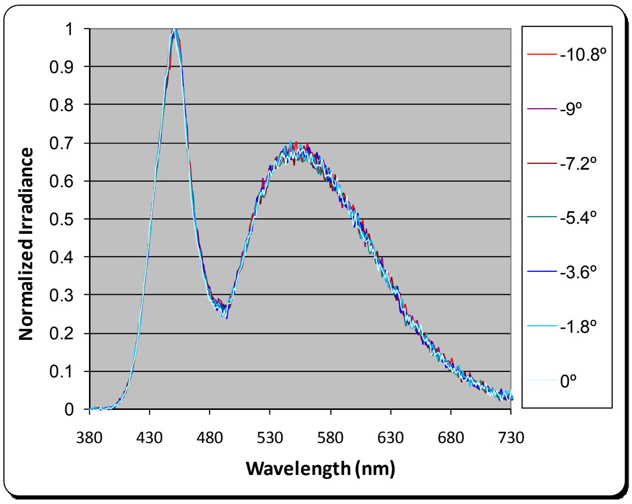



*Figure 7. Brand2 white LED 140º normalized spectral irradiance (W/m2) at different viewing angles. Data of angles higher than 10.8º have been omitted for comparison with the Brand1 white LED 20º.*

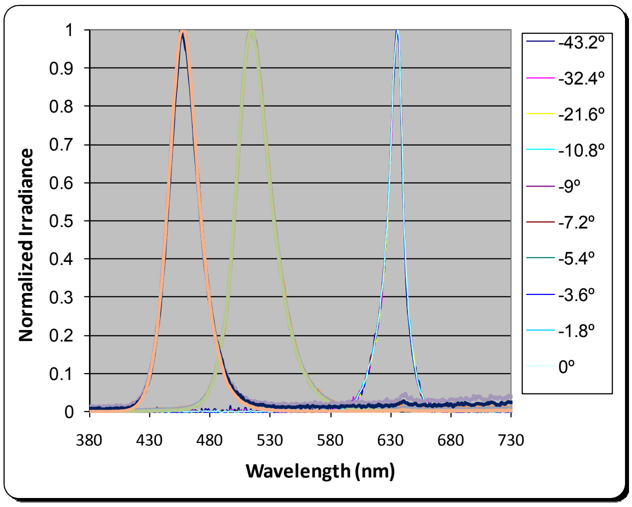



***Figure 9**. 3 Single color LEDs (Brand1 Red LED 20º, Brand2 Green LED 20º, Brand3 Blue LED 20º) normalized spectral irradiance (W/m$^2$) at different viewing angles.*

Besides the white LEDs, different single color LEDs were also analyzed to assess the spectral irradiance change with the viewing angle. Most single color LEDs maintained a constant spectrum independently of it, with changes in the chromaticity coordinates (CIE-1931 standard observer) similar or smaller than 0.001 ($\Delta x$, $\Delta y$). Figure 9 shows the normalized spectral irradiance of three representative LEDs (blue, green, and red) with 20º directivity patterns from different manufacturers at different viewing angles. Nevertheless, we have found two single color LEDs that do not follow this pattern, and they are illustrated in figure 10. However, it can be concluded that in general the spectral changes of all single color LEDs with the angle are very subtle compared to those obtained in white LEDs with similar directivity patterns.

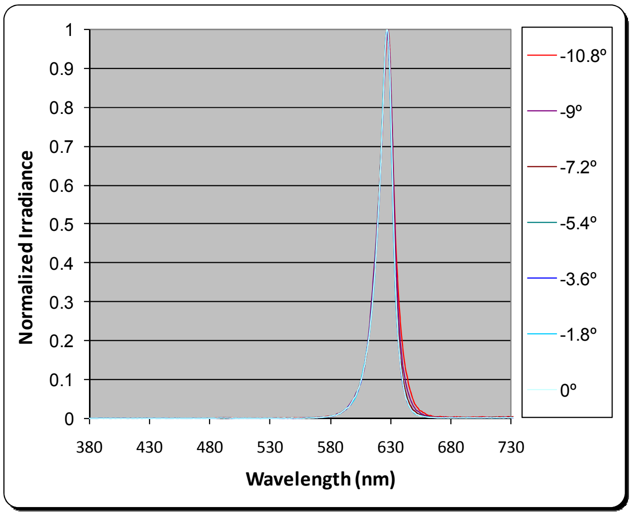
**Table 1. Differences of CIE 1931-xy chromaticity coordinates (Δx,Δy) between 0º and the rest of angles (#º) of the white LEDs. Results are given for all white LEDs as well as for those with narrow (≤70º) and broad (>70º) directivity patterns.**

$\Delta x = |x(\#^\circ) - x(0^\circ)|$ , $\Delta y = |y(\#^\circ) - y(0^\circ)|$

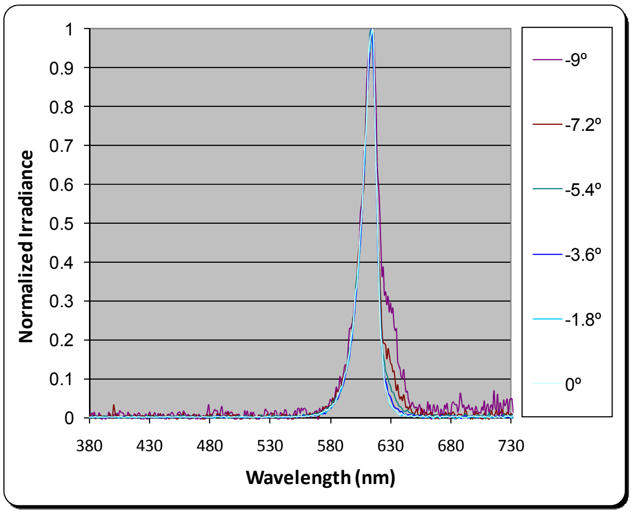
| Angle (º) | All directivities | Directivity ≤ 70º | Directivity > 70º |
|---|---|---|---|
| 0.0 | 0.000, 0.000 | 0.000, 0.000 | 0.000, 0.000 |
| 1.8 | 0.001, 0.002 | 0.001, 0.002 | 0.001, 0.002 |
| 3.6 | 0.003, 0.005 | 0.004, 0.006 | 0.001, 0.002 |
| 5.4 | 0.007, 0.012 | 0.010, 0.016 | 0.001, 0.002 |
| 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 |

Finally, to assess the importance of the spectral power distribution change with the viewing angle, we analyzed the spectral and color accuracy of a commercially available spectrophotometric system using a white LED as a light source. The results obtained when measuring with the spectrophotometric system a white ceramic tile surface at different angles and distances provided the CIEDE2000 color differences, with respect to the measurement at the nominal position, shown in figure 11.

From the CIEDE2000 analysis, it can be seen that the color accuracy degradation is almost symmetrical to angle and it gets worse the further it is from the ideal (nominal) position. Approximately the same behavior can be seen when analyzing the changes in the lightness coordinate (ΔL*) independently. As expected, measurements performed at rotated positions and at closer or further distances from the nominal position provide spectral results above or under the one obtained at the nominal position, since the overall amount of light reaching the white ceramic tile changes.




(a)




(b)

***Figure 10**. Single color LEDs normalized spectral irradiance (W/m$^2$) at different viewing angles: (a) Brand1 Red 20º (b) Brand1 Amber 20º.*

On the other hand, the variability of the a* coordinate (Δa*) with the rotation angle and distance is very low. However, meanwhile changes with angle of the b* coordinate (Δb*) are also small, relevant symmetrical changes with distance are observed in this case, independently if the sample gets closer or further from the nominal position. Because Δa* and Δb* variability was different, the following conclusions could be reached: when a 45/0 spectrophotometer architecture is used, a change in the sample to instrument distance also means a change in the illumination angle (Φ), even more when a point light source is used (see Figure 1). Then, if the emitted spectrum of the white LED changes with 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 from that at the nominal position, and for this reason, the color accuracy of the spectrophotometric system degrades with the distance. If Δb* changes and Δa* stays almost the same, this means that the 'yellowish' effect is the root cause of the color measurement variability found between different distances. This behavior agrees with the former results found with independent white LED analyses.

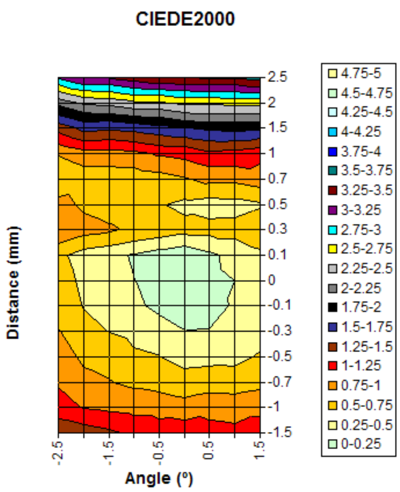
## Conclusion

White light LEDs designed with a blue emitting LED coated with a yellow emitting phosphor, emit light whose spectrum changes as a function of the viewing angle, probably as a consequence of the nature of the technology utilized by manufacturers to coat them. Analyses have demonstrated that the narrower the directivity pattern, the higher the 'yellowish' effect with the viewing angle. Therefore, if the radiant power is enough for the application, white LEDs with broad directivity patterns show more stable spectral distribution at a broad angle rotation range. For this reason, they are recommended to be used in multispectral system designs with several filters with different spectral transmittances rather than white LEDs with narrow directivity.

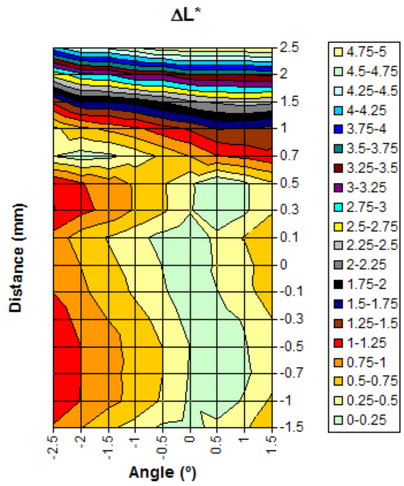
On the other hand, most single color LEDs do not show a spectrum change with the viewing angle compared to white LEDs with similar directivity patterns. Therefore, they are very advisable to be used in multispectral systems. However, as we have demonstrated, there is always the possibility of finding a single color LED with a spectrum change with the angle. Therefore, as in the case of white LEDs, an analysis for each single color LED should be always performed before deciding to use it in a multispectral system.

It has also been shown that noticeable color differences can be found with spectrophotometric systems that use a white LED due to changes in its spectral emission at different angles. Therefore, there is a need to always calibrate the illumination system with a known reference at difference angles and distances.

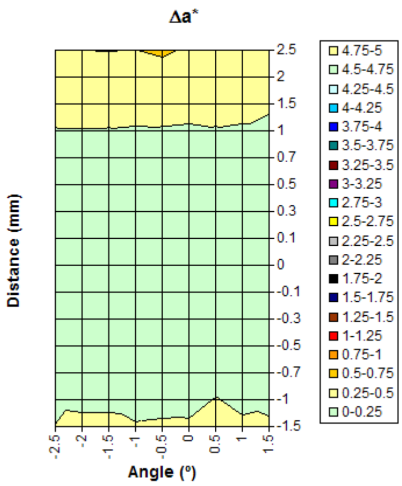
Finally, the analysis performed also reveals that currently it is very difficult to find in the market white LEDs with enough spectrum power below 400 nm. The use of single color LEDs are recommended to completely cover the visible spectrum.



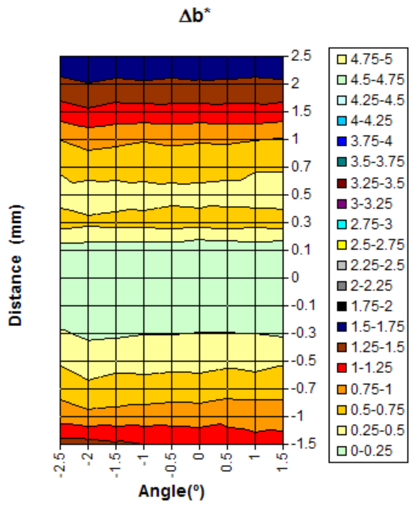

(a)




(b)




(c)




(d)

***Figure 11.*** *CIEDE200 color differences between the measurements performed on a white ceramic tile surface at different angles and distances with respect to nominal position. (a) CIEDE2000 color difference (b) Same analysis expressed only in $\Delta L^*$ changes (c) in $\Delta a^*$ changes and (d) in $\Delta b^*$ changes.*

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## Author Biography

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